PART F1

PART H1

PART J1

Ed-Lab
Text-Lab Manual

MAGNETISM and MOTORS PART F1

DIODES and POWER SUPPLIES PART H1

TRANSISTORS and CIRCUITS PART J1

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Ed-Lab
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Ed-Lab
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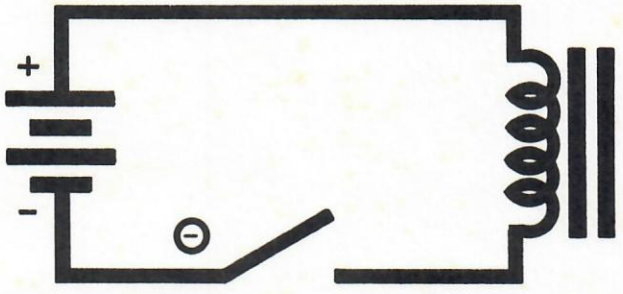
F1 - MAGNETISM and MOTORS



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ISBN 0-86711-109-7
Printed in United States of America

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PART F1 - MAGNETISM and MOTORS

Table of Contents

	Student Progress Record and Guide
	Safety Notes
Info. Sheet 1	Magnets and Magnetism
Experiment 1	Magnets
Info. Sheet 2	Electromagnetism
Experiment 2	Electromagnets (CES 318)
Experiment 3	Relays (CES 318)
Experiment 4	Latching Relay (CES 318)
Experiment 5	Burglar Alarm (CES 318)
Info. Sheet 3	Electromagnetic Induction Principles
Experiment 6	Electromagnetic Voltage Induction (CES 318)
Info. Sheet 4	DC Motors and Generators
Experiment 7	DC Motor Operation (CES 309)
Experiment 8	Generators and Motor Generator Sets (CES 309)
Info. Sheet 5	Forces and Resistances

Name _____

Class _____

School _____

STUDENT PROGRESS RECORD & GUIDE FOR PART F1

EXP./INFO	TITLE	ASSIGNMENT		GRADE
		DATE DUE	DATE SUBMITTED	
Info. Sheet 1	Magnets and Magnetism			
Experiment 1	Magnets			
Info. Sheet 2	Electromagnetism			
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Experiment 5	Burglar Alarm			
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Experiment 6	Electromagnetic Voltage Induction			
Info. Sheet 4	DC Motors and Generators			
Experiment 7	DC Motor Operation			
Experiment 8	Generators and Motor Generator Sets			
Info. Sheet 5	Forces and Resistances			

Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part E1 and G1. Review this lesson.

Ed-Lab
TEXT-LAB MANUAL
MAGNETISM and MOTORS
PART F1

Magnets and Magnetism

INFO SHEET 1

OBJECTIVES

When you complete this information sheet you will be able to:

1. Describe the earth's magnetic field.
2. Explain the operation of a magnetic compass.
3. Describe the magnetic field around a bar magnet.
4. List seven rules of behavior for the magnetic lines of force that surround a magnet.
5. Define a magnet and identify its poles.
6. State the rules for magnetic attraction and repulsion.
7. Describe the Dipole and Domain theories of magnetism.
8. Define Ferromagnetic, Paramagnetic and Diamagnetic materials.
9. Explain what is meant by permeability.

DISCUSSION

The subject of magnetism is important in electrical and electronic studies because it makes it possible to understand the generation and distribution of electricity, the operation of motors and even the operation of radio and television devices.

ANCIENT DISCOVERIES

The earliest record relating to magnetism is in 600 B.C. when Thales, a Greek philospher, wrote of the attraction between certain stones. These stones were first found in Magnesia, in Asia Minor, from which the word "magnet" is derived. The stones, now called "magnetite," were called "lodestones" which meant "leading stone" because, when suspended from a string they always rotated to point in the same direction, namely North and South. The Chinese used the lodestones for navigation in approximately the year 1200.

It was in 1600 that Dr. William Gilbert showed that the earth was like a large magnet. The pieces of magnetite lying on or just below the earth's surface became magnetized by the earth's magnetic field.

EARTH'S MAGNETIC FIELD

The earth has an invisible magnetic field consisting of magnetic lines of force, called Magnetic Flux, between the North and South poles. This is shown in Figure 1 where it can be seen that the magnetic axis of the earth is located about 15 degrees from the geographical poles.

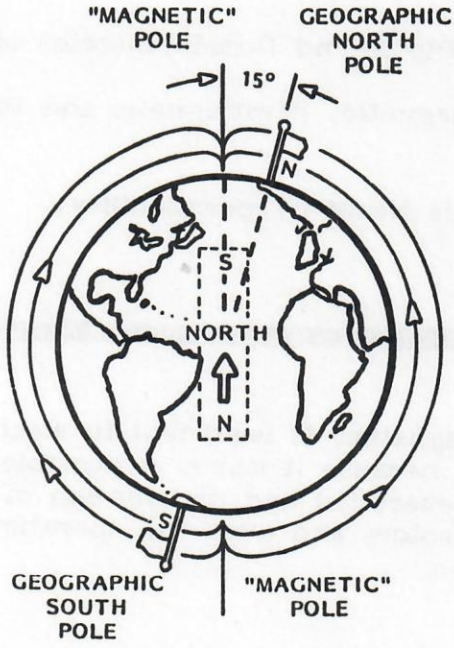


Figure 1 - The earth as a magnet. The magnetic and geographical poles are located a considerable distance apart.

The magnetic lines of force flow out of the magnetic South pole, around the earth, and reenter at the magnetic North pole. These lines of force cover the entire earth's surface for a full 360 degrees.

COMPASS

A compass consists of a small magnet mounted on a pivot so that it is free to rotate. When this compass is placed in the earth's magnetic field its magnet rotates to align itself with the magnetic field as shown in Figure 2(a). The end of the compass magnet, marked N for North, will point to the North magnetic pole.

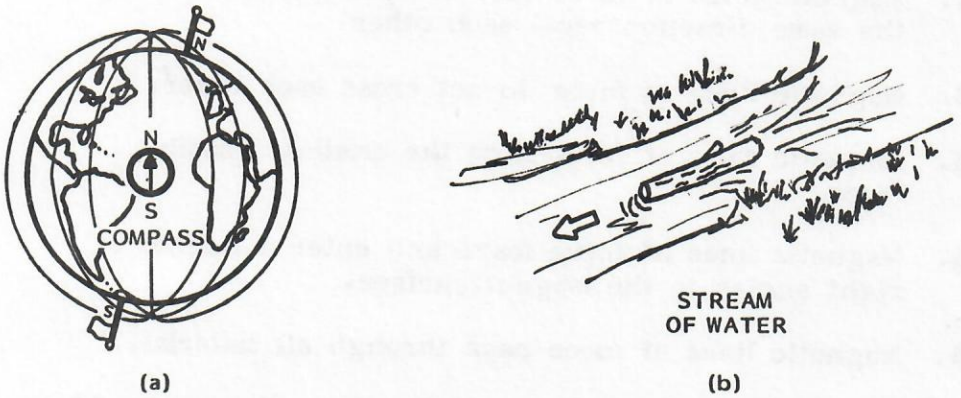


Figure 2(a) - Compass responding to Earth's magnetic field.
(b) - Log in a stream of water aligns with direction of flow.

The alignment of the compass needle is similar to a log that positions itself with the flow of water in a stream as shown in Figure 2(b). The compass needle positions itself in the flow of magnetic lines of flux. Although the magnetic compass operates on different forces than the mechanical forces acting on the log, it is as real a force even though invisible.

MAGNETS

A most common magnet is the "bar magnet" pictured in Figure 3. It also has invisible lines of force around it, the same as those existing around the earth.

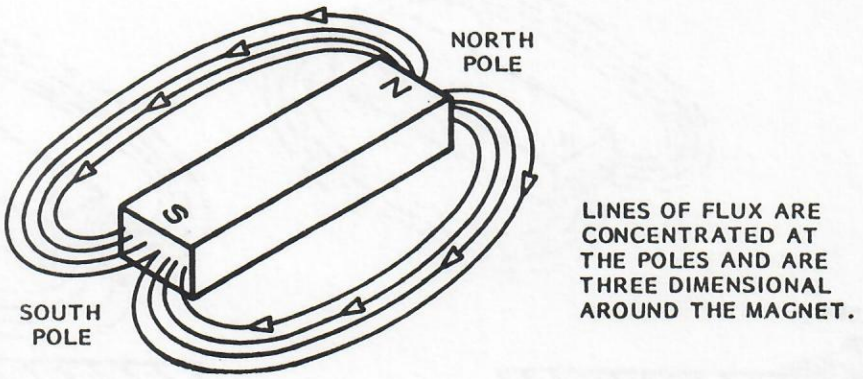


Figure 3 - Bar magnet and its magnetic field.

Why the field is shaped as shown in Figure 3 can be understood from the following rules that describe the behavior of lines of force.

1. Magnetic lines of force always form closed loops. This means that a line of force that leaves one end of the magnet reenters at the other end of the magnet.

2. Magnetic lines of force that are parallel and moving in the same direction repel each other.

3. Magnetic lines of force do not cross each other.

4. Magnetic lines of force form the smallest possible loops.

5. Magnetic lines of force leave and enter a magnet at right angles to the magnet surface.

6. Magnetic lines of force pass through all material.

7. Magnetic lines of force have direction; they are said to flow out of the North pole into the South pole.

The bar magnet exhibits magnetic properties which may be defined as follows.

> MAGNETISM is the property of a material that permits it to attract certain metals such as iron or steel. A material that posses this property is called a magnet.

Consider the magnetic action shown in Figure 4(a). Several iron or steel screws are placed at some distance below a magnet where the magnetic field is weak. The screws are too far away to be influenced by the magnetic field.

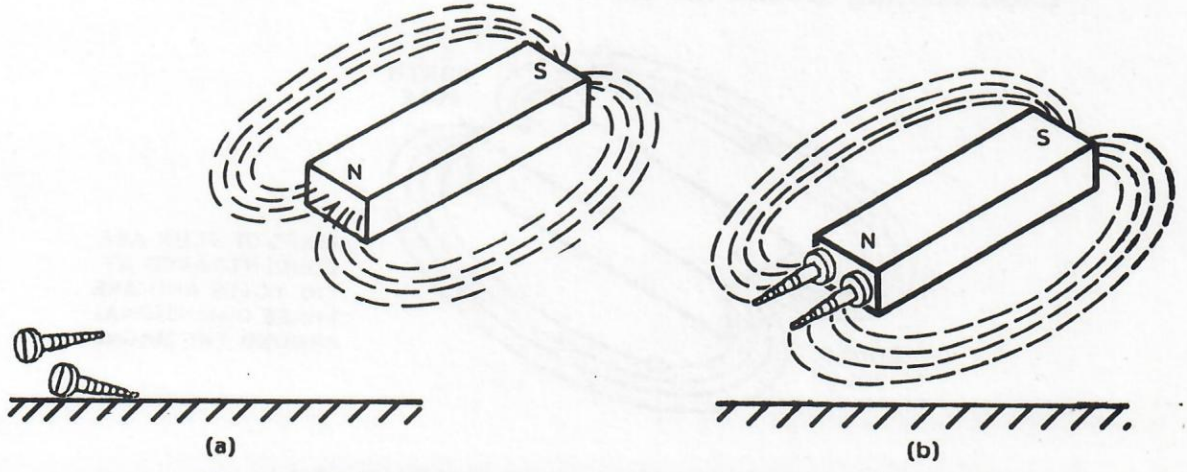


Figure 4(a) - Screws too far from magnetic field to respond. (b) - Closer field draws screws to magnet.

When the magnet is brought closer to the screws as in Figure 4(b), the field affects the screws and the magnetic force "draws" or lifts the screws, against gravity, up to the magnet.

IRON FILINGS AND LINES OF FORCE

Although magnetic lines of force are invisible, their pattern or shape can be seen by using very small pieces of iron called "filings." If a magnet is covered with a sheet of paper or a pane of glass and these iron filings are sprinkled over the glass, the filings will align themselves with the magnetic field and the actual shape, concentration and pattern of the field will be displayed. This is shown in Figure 5.

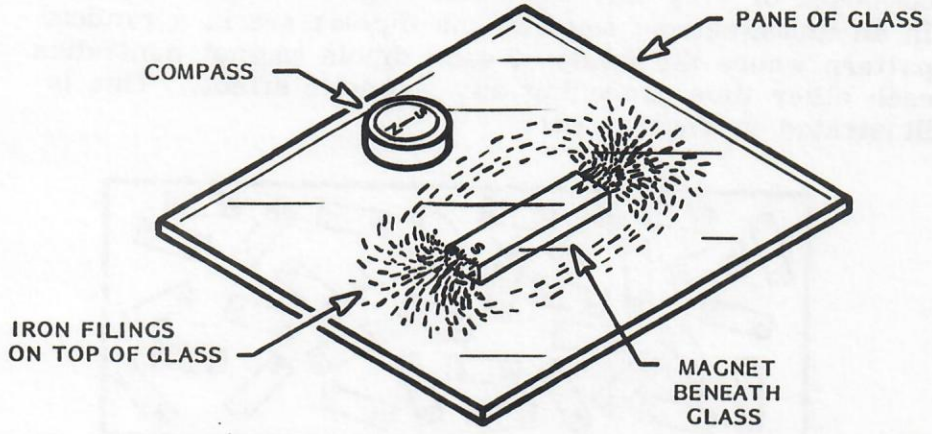
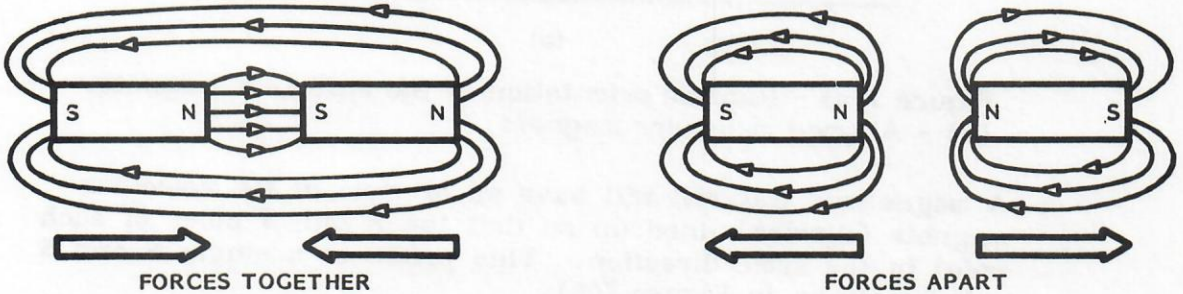


Figure 5 - Iron filings used to show magnet's field pattern.

MAGNETIC POLARITY

A magnetic field consists of lines of force that are said to radiate from the North pole and flow to the South pole of the magnet as shown earlier in Figure 3. When two unlike magnetic poles are brought together as shown in Figure 6(a), the lines of force pass through both magnets and the magnets are drawn together.



(a) UNLIKE POLES ATTRACT (b) LIKE POLES REPELL

Figure 6(a) - Unlike magnetic poles attract when close.
(b) - Like poles repel when close.

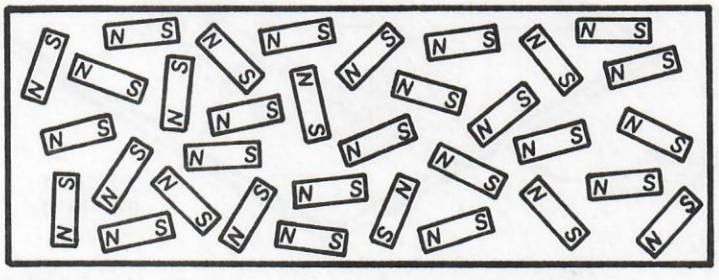
When two identical magnetic poles are brought together (Figure 6(b)) the lines of force repel each other and push the magnets apart. The forces of attraction and repulsion are greatest when the magnets are brought closer together.

THEORIES OF MAGNETISM

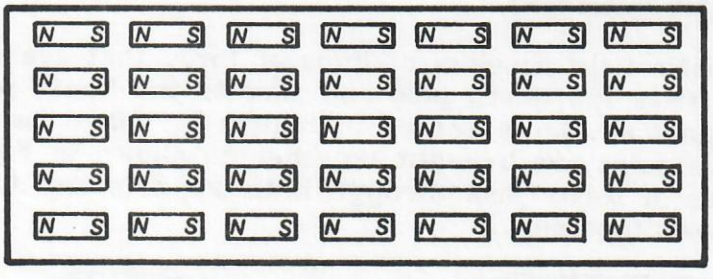
There are two theories or explanations given to explain magnetism. These are:

1. The Dipole Theory
2. The Electron Spin or Domain Theory.

The "Dipole" theory assumes that all magnetic substances are composed of very tiny molecular magnets called "dipoles." In an unmagnetized material the dipoles are in a random pattern where the fields of each dipole magnet neutralize each other thus cancelling any magnetic effect. This is illustrated in Figure 7(a).



(a)



(b)

Figure 7(a) - Random orientation of the molecular magnets. (b) - Aligned molecular magnets

A magnetized material will have all or most of its molecular magnets (dipoles) lined up so that the N and S poles of each point in the same direction. This produces a single N and S pole as shown in Figure 7(b).

Based on the Dipole" theory it is possible to understand what happens when a bar magnet is divided into smaller and smaller sections as shown in Figure 8. Each section of the magnet is found to posses a N and S pole with the polarities in the same orientation as the original magnet.

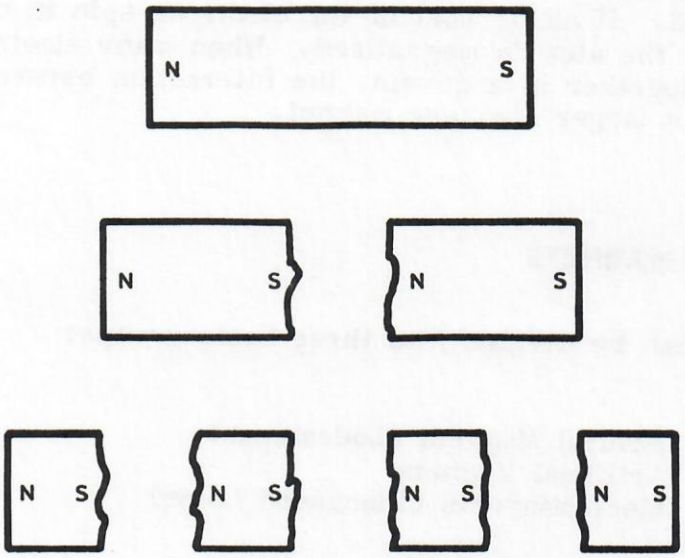


Figure 8 - Dividing a magnet results in smaller magnets with the same polarity.

ELECTRON SPIN OR DOMAINS

Another more modern theory of magnetism is based on the electron spin principle illustrated in Figure 9 below.

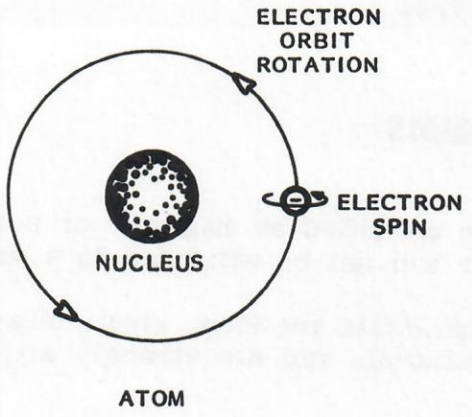


Figure 9 - Electron spin in an atom.

It is theorized that electrons spin in their own axis as they orbit the nucleus of an atom and that each electron is surrounded by its own magnetic field. The total magnetic field of an atom is determined by the direction of spin of all the electrons. If an atom has an equal number of electrons spinning in opposite directions, the magnetic fields of the electrons cancel and the atom is not magnetized. If all or most of the electrons spin in one direction, the atom is magnetized. When many electrons are grouped together in a domain, the interaction between them produces a larger stronger magnet.

TYPES OF MAGNETS

Magnets can be divided into three basic groups:

1. Natural Magnets (Lodestones)
2. Artificial Magnets
3. Electromagnets (Discussed Later)

An artificial magnet is created by placing a metal in a magnetic field so that it becomes magnetized. When the magnetic field is removed and the metal remains magnetized, it is a "permanent" magnet. Hard steel and ALNICO will become permanent magnets. ALNICO is an alloy of aluminum, nickel, cobalt and iron.

If the magnetic field is removed and the metal loses its magnetism it is then a "temporary" magnet. Soft iron is a material of this type.

MAGNETIC MATERIALS

All matter can be classified as magnetic or non-magnetic, that is, it will or will not be attracted to a magnet.

FERROMAGNET materials are iron, steel, nickel, cobalt and alloys of these materials and are strongly attracted by magnets.

PARAMAGNETIC materials are only slightly attracted to a magnet and these include air, aluminum and liquid oxygen.

DIAMAGNETIC materials are those slightly repelled by a magnet and include copper, quartz and silver.

Because it is so hard to magnetize paramagnetic and diamagnetic materials they must be considered, for practical purposes, non-magnetic.

If a ferromagnetic material such as soft iron is placed in a magnetic field as shown in Figure 10, it will divert or distort the field as shown. Observe that the passage of lines of force through the soft iron magnetize it temporarily to the polarity shown.

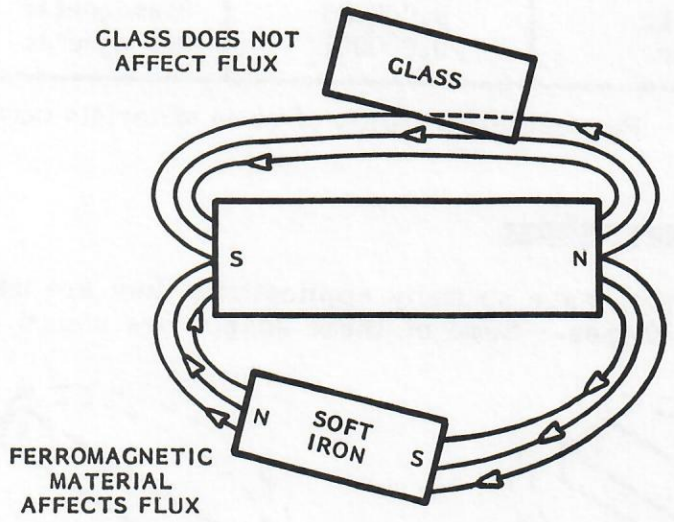


Figure 10 - Effects of soft iron on a magnetic field.

PERMEABILITY

The ability of a material to conduct magnetic lines of force is defined as PERMEABILITY and its symbol is the Greek letter μ. The higher the permeability rating of a material, the better it conducts magnetic lines of force. Ferromagnetic materials are highly permeable because magnetic lines of force pass through them with ease.

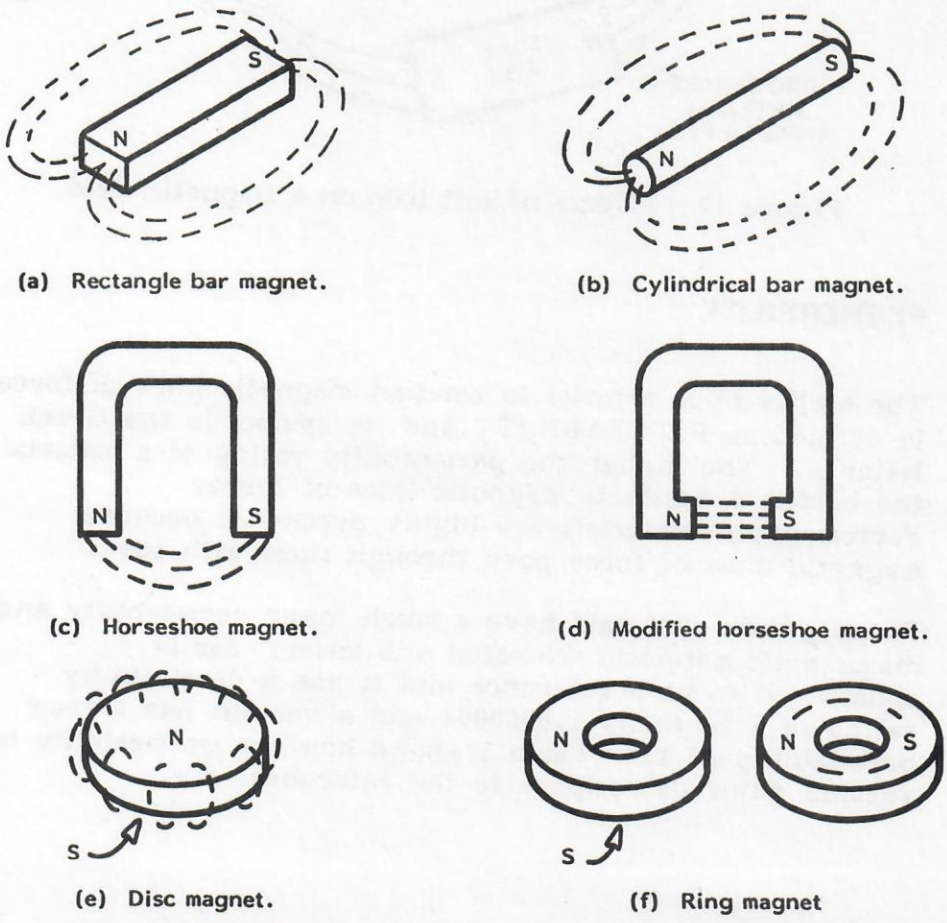
Paramagnetic materials have a much lower permeability and diamagnetic materials are rated still lower. Air is considered to be a reference and it has a permeability rating of 1 (actually 1.0000004 and a vacuum has a true permeability of 1). Table 1 shows how the permeability of various materials compare to the reference, air.

MATERIAL	PERMEABILITY (μ)	TYPE
Supermalloy	1,000,000	Ferromagnetic
Permalloy	100,000	Ferromagnetic
Iron	7,000	Ferromagnetic
Nickle	1,000	Ferromagnetic
Cobalt	170	Ferromagnetic
Aluminum	1.0000214	Paramagnetic
Air	1.0000004	Paramagnetic
Vacuum	1.0000000	Paramagnetic
Copper	0.999995	Diamagnetic
Quartz	0.000085	Diamagnetic
Water	0.000001	Diamagnetic

TABLE 1 - Permeability ratings of some materials compared to air.

OTHER MAGNET SHAPES

Because magnets have so many applications they are made in a variety of shapes. Some of these shapes are shown in Figure 11.



(a) Rectangle bar magnet.

(b) Cylindrical bar magnet.

(c) Horseshoe magnet.

(d) Modified horseshoe magnet.

(e) Disc magnet.

(f) Ring magnet

Figure 11 - Magnet shapes

The bar magnets have already been described. The horseshoe magnet is basically a bar magnet formed into a U shape. Bringing the N and S poles closer together strengthens the magnetic field. Adding pole piece extenders to the modified horseshoe magnet in (d) of Figure 10 brings the poles even closer together resulting in a very strong field. This type of magnet is used for meter movements that were described in Module 1, Unit D4, Experiment 25, Figure 4(b).

The disc and ring magnets can be pictured as a thin cross section slice of the cylindrical bar magnet shown in Figure 11(b).

CONCLUSIONS

We have learned from this information sheet that:

A magnetic field surrounds the earth.

The magnetic lines of force are considered to leave the magnetic pole at the North and flow to the magnetic pole at the South.

The magnetic and geographic poles are approximately 15 degrees apart.

The pointer of a compass will align itself with the earth's magnetic field and point North-South.

A bar magnet has a magnetic field similar to earth's but much weaker.

Magnetic lines of force behave according to specific rules.

Like magnetic poles repel, unlike magnetic poles attract.

Electrons are surrounded by a magnetic field.

Magnets are made in a variety of shapes.

Ferromagnetic materials are strongly attracted by magnets.

Paramagnetic materials are slightly attracted by magnets.

Diamagnetic materials are slightly repelled by magnets.

Permability is a measurement of the ease with which magnetic lines of force flow through a material.

Air has a permeability of 1 and ferromagnetic substances can achieve permeability ratings up to and greater than one million.

ASSIGNMENT

Answer the following multiple choice questions.

1. A magnet has cross-section of 1" x 3/4" and a length of 4". It can best be defined as a(n):

   a. natural magnet.
   b. horseshoe magnet.
   c. bar magnet.
   d. electromagnet.

2. A permanent magnet can be made from:

   a. soft iron.
   b. steel.
   c. aluminum.
   d. any of the above.

3. The pattern of the magnetic field surrounding a magnet can be shown by placing the magnet under a pane of glass and sprinkling one of the following materials on the glass:

   a. sawdust.
   b. aluminum filings.
   c. bits of paper.
   d. iron filings.

4. The magnetic field of a bar magnet is most powerful at:

   a. the North Pole.
   b. the South Pole.
   c. both poles.
   d. the center of the bar.

5. Magnetic lines of force:

   a. form closed loops that are as small as possible.
   b. enter and leave a magnet at right angles to the surface.
   c. pass through all materials.
   d. all of the above.

6. Magnetic lines of force:

   a. cross each other when possible.
   b. flow from N to S.
   c. are blocked by soft iron.
   d. repel each other if the facing poles are of opposite polarity.

7. When the N and S poles of two magnets are brought close to each other, they:

   a. repel.
   b. attract.
   c. cancel the lines of force.
   d. none of the above.

8. When a bar magnet is bent into a U shape, the magnetic field betwen the poles will be:

   a. stronger.
   b. weaker.
   c. cancelled.
   d. unaffected.

9. Iron can best be defined as:

   a. Diamagnetic.
   b. Paramagnetic.
   c. Ferromagnetic.
   d. a material used for permanent magnets.

10. Material A has a permeability of 2,560 and material B has a permeability of 1,550. The best permanent magnet can be made from:

    a. Material A.
    b. Material B.
    c. neither material A or B.
    d. either material A or B.

11. Diamagnetic materials, when placed in a magnet field, are:

    a. strongly attracted.
    b. strongly repelled.
    c. slightly attracted.
    d. slightly repelled.

12. Paramagnetic materials, when placed in a magnetic field, are:

    a. strongly attracted.
    b. strongly repelled.
    c. slightly attracted.
    d. slightly repelled.

13. Ferromagnetic materials, when placed in a magnetic field, are:

    a. strongly attracted.
    b. strongly repelled.
    c. slightly attracted.
    d. slightly repelled.

14. When a bar magnet is cut in half:

    a. it will become demagnetized.
    b. one half will be the S pole and the other half the N pole.
    c. each half will become a separate magnet with a N and S pole.
    d. none of the above.

15. One theory of magnetism states that when the molecular dipoles of a material are not aligned (in disarray) the material is:

a. not magnetized.
b. fully magnetized.
c. can never be magnetized.
d. none of the above.

KEY TERMS

1. ALLOY

   A mixture of two or more elements, at least one of which is a metal.

2. DIAMAGNETIC

   A material that becomes weakly magnetized but in the opposite direction to that of the magnetizing force resulting in a repelling effect.

3. ELECTROMAGNET

   A magnet produced by the flow of current through a wire.

4. FERROMAGNETIC

   A material that becomes strongly magnetized when placed in a magnetic field.

5. MAGNET

   A material that attracts iron and steel.

6. MAGNETIC FIELD

   The invisible lines of force that surround a magnet.

7. MU (μ)

   The symbol for permeability.

8. PARAMAGNETIC

   A material that becomes slightly magnetized when placed in a magnetic field.

9. PERMEABILITY (μ)

   The measure of how much better a material conducts magnetic lines of force as compared to air which has a μ of 1, approximately.

Magnets 1

OBJECTIVES

When you complete this experiment you will be able to:

1. Use a compass to locate the direction of the magnetic North pole.
2. Demonstrate the effect of a lodestone on a compass and use the lodestone as a compass.
3. Determine which objects are ferromagnetic using a bar magnet.
4. Verify the laws of magnetic attraction and repulsion.
5. Display the magnetic field pattern of a bar magnet.
6. Demonstrate how soft iron affects a magnet's field pattern.

ADDITIONAL EQUIPMENT

(Equipment is optional and not provided with the Ed-Lab 651. Experiments may be for demonstration only.)

1 - Lodestone
1 - Compass
1 - Horseshoe Magnet
2 - Bar Magnets
1 - Container of Iron Filings
1 - Piece of soft iron half the length of the bar magnet
4 - Assorted magnetic and non-magnetic materials
1 - Stand and string (Optional)
1 - Clear plastic box
1 - Oscilloscope

DESCRIPTION

This experiment requires many additional parts and may best be done as a demonstration rather than an experiment. As a demonstration, as well, it is totally or partially optional as the material covered is concerned with basics of Physics.

The theory involved in this experiment has been covered in Information Sheet No. 1 which should be read before performing the procedure below. The procedure consists of 10 parts that are clearly described, step by step.

PROCEDURE WARNING

When following the procedure, keep all the magnets away from personal watches. Many will stop running when magnetized and will have to be demagnetized.

PROCEDURE

1. Draw the layout of your lab or classroom in the space provided below. Only the perimeter outline is necessary.

   Show the window locations on the drawing.

   Indicate the direction of true magnetic North with relation to the room if it is known.

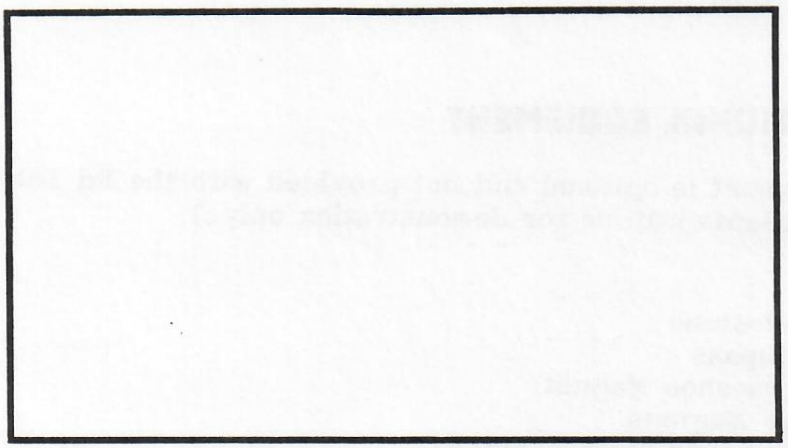


Figure 1 - Room layout drawing.

1.1 COMPASS OPERATION

2. Take a compass reading at four separate locations in the room.

3. Record the directions of each compass reading on the room layout of Figure 1.

   Do all the compass readings point in the same direction? _____

If they do not, why do you think this is so? _____

_____

_____

Are any of the compass readings to true magnetic North? ____

_____

_____

1.2 LODESTONE

4. Bring a lodestone close to the compass to observe its effect on the pointer.

   Rotate the lodestone so that it alternately attracts and repels the N pole (black) of the compass pointer.

   Does the lodestone have a magnetic field about it? _____

   _____

   Does the lodestone have a North and South pole? _____

   _____

5. Tie a string to the lodestone and suspend the lodestone over the bench or desk using a support as shown in Figure 2.

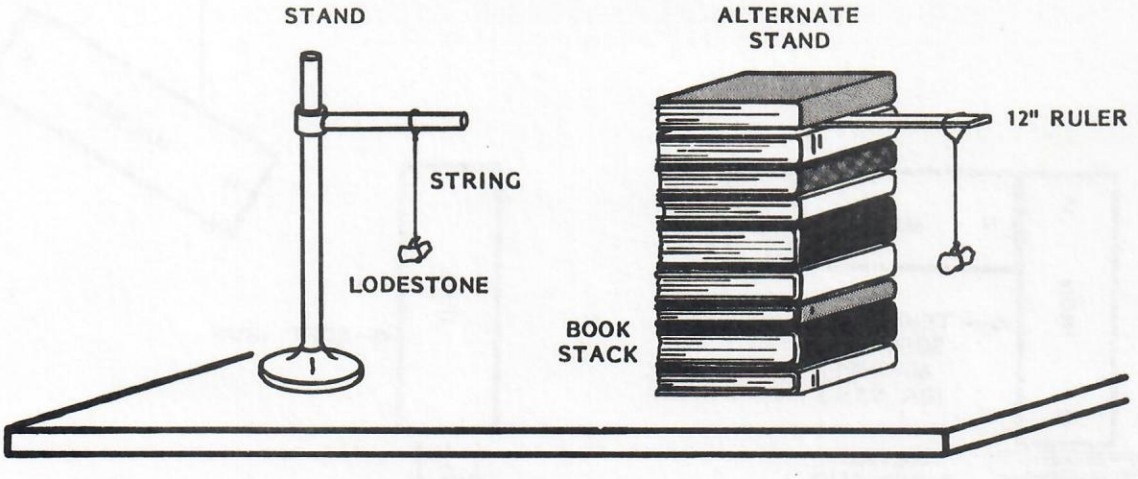


Figure 2 - Lodestone suspended from a stand and an alternate form of stand.

Allow the lodestone to stablized. Note the direction in which it points when it is still.

Move the lodestone and again wait for it to stablize. Does it return to the same North-South position? _____

_____

1.3 BAR MAGNET

6. Use the bar magnet to attract the various substances. List the substances below and indicate if or not they are attracted to the magnet.

	SUBSTANCE	ATTRACTED
a.		
b.		
c.		
d.		

1.4 TEMPORARY MAGNET

7. Place the piece of soft iron at the end of the bar magnet as shown in Figure 3(a). The magnetic lines of force create a temporary magnet as shown.

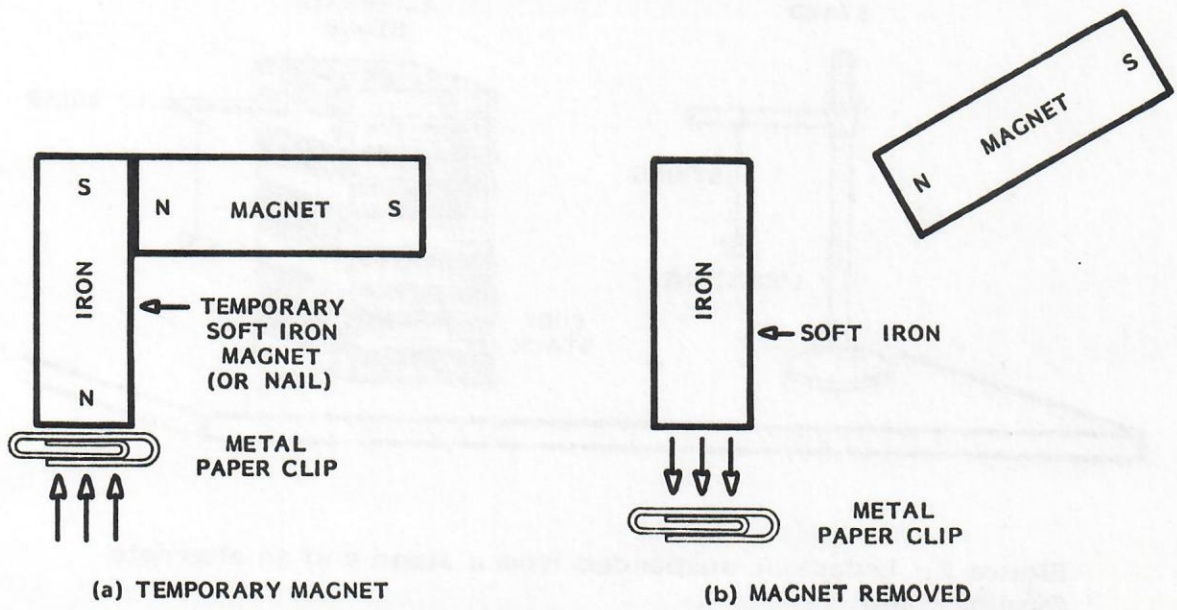


Figure 3 - Temporary soft iron magnet.

8. Pick up several ferromagnetic metals with the end of the temporary magnet.

9. Remove the bar magnet from the soft iron while it is suspending ferromagnetic material (Figure 3 (b)). What happens to the suspended objects? Why? _____

_____

1.5 MAGNETIC FIELD STRENGTH

10. Position a bar magnet on the bench as shown in Figure 4 below.

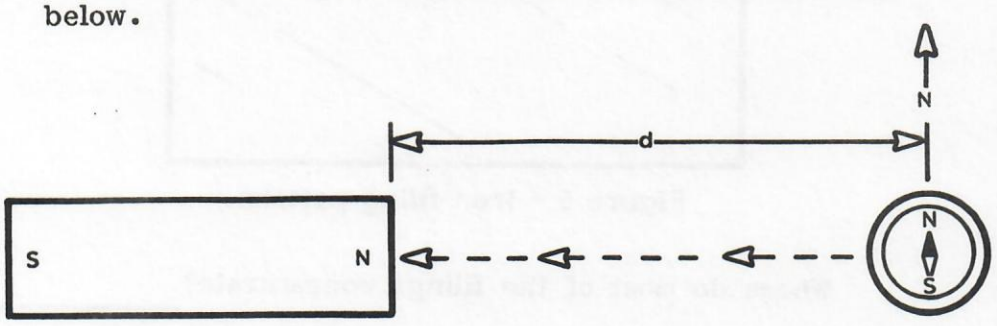


Figure 4 - Bar magnet and compass.

11. Place a compass at the North end of the magnet far enough away so that the compass points to the true magnetic North pole.

    Gradually slide the compass toward the bar magnet and measure the distance, d in Figure 3, where the compass first responds to the bar magnet.

    Response distance, d: _____

1.6 MAGNETIC FIELD PATTERN

12. Place a clear plastic box over a bar magnet as shown in Figure 5 below.

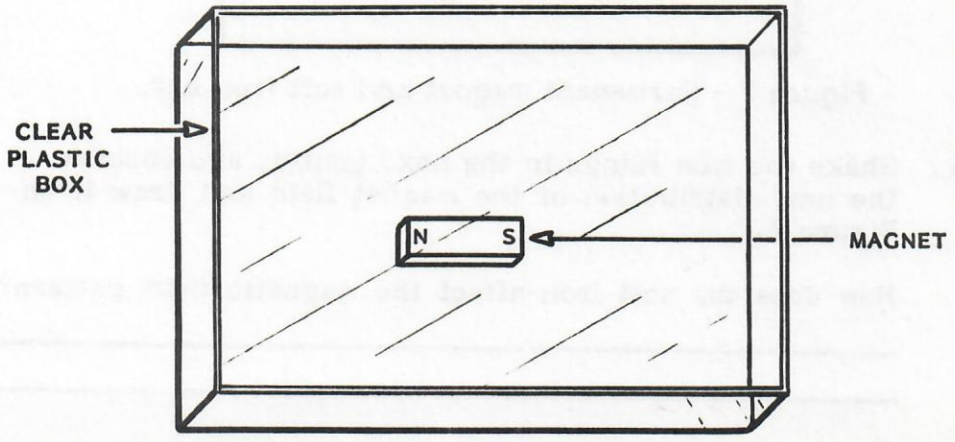


Figure 5 - Clear plastic box over a bar magnet.

13. Sprinkle iron filings inside the box and shake the box gently to position the filings.

Draw the pattern formed by the filings in the outline of Figure 6.

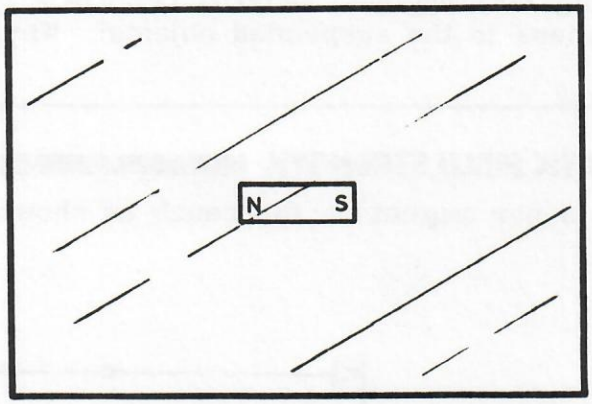


Figure 6 - Iron filing pattern.

Where do most of the filings concentrate? _____

_____

1.7 SOFT IRON PATTERN

14. Remove the iron filings temporarily.

Place the soft iron bar or nail under the plastic box as shown in Figure 7.

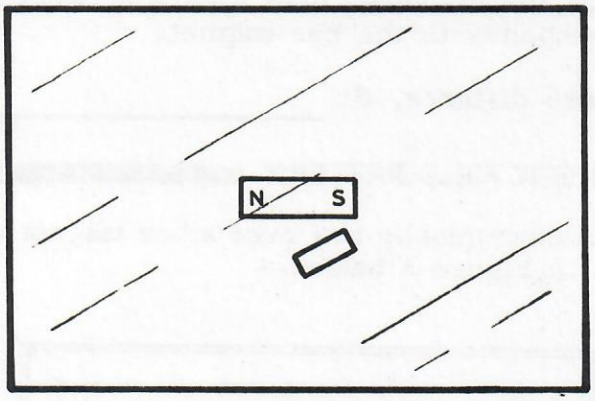


Figure 7 - Permanent magnet and soft iron bar.

15. Shake the iron filings in the box, gently, and observe the new distribution of the magnet field and draw it on Figure 7.

How does the soft iron affect the magnetic field pattern?

_____

_____

1.8 HORSESHOE MAGNET PATTERN

16. Place a horseshoe magnet under the plastic box.

    Shake the iron filings in the plastic box so that the magnetic field is outlined.

17. Draw the field pattern in the space provided below in Figure 8.

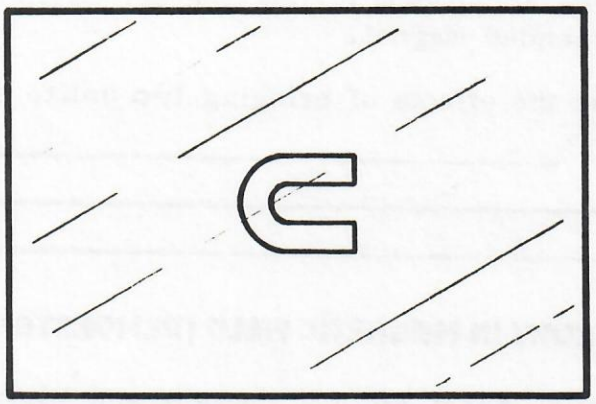


Figure 8 - Iron filing field pattern of a horseshoe magnet.

How does the magnetic field pattern of the horseshoe magnet differ from that of the bar magnet? Where is the field strongest?

_____

_____

_____

1.9 MAGNETIC ATTRACTION AND REPULSION

18. Suspend one bar magnet from the stand at the end of the string as shown below in Figure 9.

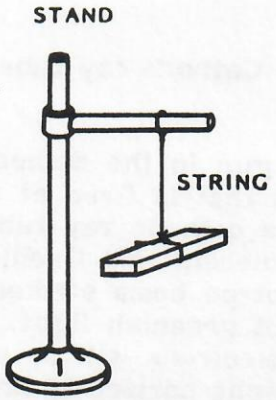


Figure 9 - Suspended bar magnet.

19. Bring one pole of the second bar magnet close to the identical pole of the suspended bar magnet.

Describe the effect of bringing two like poles together. _____

_____

_____

20. Bring the unlike pole of the free bar magnet close to the suspended magnet.

Describe the effects of bringing two unlike poles together. _____

_____

_____

1.10 ELECTRONS IN MAGNETIC FIELD (DEMONSTRATION)

Information Sheet No. 1, "Magnets and Magnetism," presented the Domain theory of magnetisim that theorized the spin on electrons produced a magnetic field. The direction of the spin determines the polarity of the magnetic field.

Because electrons have a magnetic field about them they will respond to a second magnetic field. How this field is positioned is illustrated in Figure 10 below.

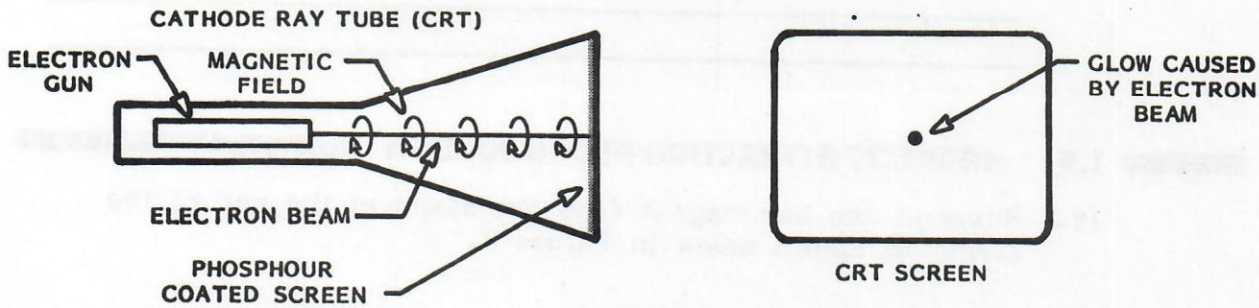


Figure 10 - Cathode ray tube (crt) and electron beam.

The electron gun in the cathode ray tube forms an electron beam that is fired at the phosphour coated screen. (The cathode ray tube is studied later when Alternating Current and Oscilloscopes are covered.) When the electron beam strikes the screen it causes a visible glow of greenish light. For this experiment, the beam of electrons will be swept back and forth to produce a bright horizontal line as shown in Figure 11.

Because the beam of electrons are all traveling in the same direction, the magnetic field of the beam is relatively strong. Thus, when the electron beam is influenced by an external magnetic field, the beam will move and the glow on the screen will show this movement.

21. Set up an oscilloscope for a straight line trace position in the center of the screen as shown in Figure 11.

Set the TIME/CM switch to 1 mS.

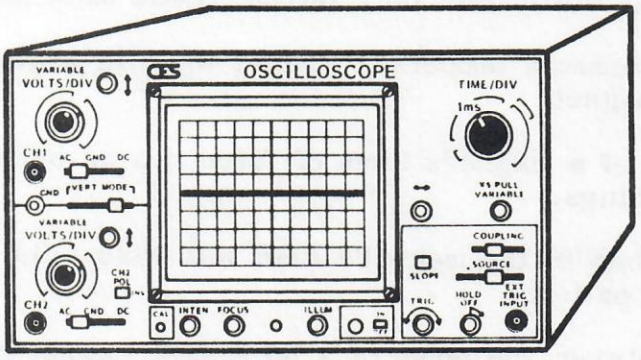


Figure 11 - Oscilloscope display.

22. Bring the N end of the bar magnet close to the center of the bright line on the oscilloscope screen.

Describe the effect upon the line. _____

_____

_____

23. Reverse the polarity of the bar magnet and bring it up to the center of the line. Describe the effect and compare it to that experienced in step 22. _____

_____

_____

_____

24. Explain how this reinforces the theory that electrons have a magnetic field around them. _____

_____

_____

_____

CONCLUSIONS

We have learned from this experiment that:

A compass directional reading taken indoors can be influenced by the steel beams in the building structure.

Natural magnets, called lodestones, will act as crude compasses.

A bar magnet, when suspend on a string will align itself with the earth's magnetic field.

A bar magnet will attract only ferromagnetic materials.

Soft iron becomes a temporary magnet when in contact with a permanent magnet.

The pattern of a magnet's lines of force can be outlined using iron filings.

A soft iron bar in the magnet's field will distort the normal field pattern.

The field between the poles of a horseshoe magnet is more intense than an equivalent bar magnet because the poles are closer together.

Like magnetic poles repel and unlike magnetic poles attract.

The electron beam of a cathode ray tube in an oscilloscope will respond to an external magnetic field.

ASSIGNMENT

Answer the following True-False questions.

1. The steel structure of a building and other surrounding metal objects do not affect the accuracy of a compass. _____

2. A bar magnet will attract all diamagnetic materials strongly. _____

3. Ferromagnetic materials are more responsive to magnetic fields than are paramagnetic substances. _____

4. A length of soft iron extends a magnet when placed in contact with one of the poles. _____

5. The more powerful a magnet is the greater the distance over which it will affect a compass. _____

6. The field pattern of a magnet can be distorted when a paramagnetic substance is brought close to the magnet. _____

7. The horseshoe magnet has a strong field between its poles because the poles are close together. _____

8. Like poles attract, unlike poles repel. _____

9. The electron beam of an oscilloscope cathode ray tube can be moved by a magnetic field. _____

10. Reversing the polarity of the external magnet will cause the cathode ray tube beam to move in the opposite direction. _____

KEY TERMS

1. BAR MAGNET

   A material, shaped in the form of a bar, that attracts iron and steel.

2. COMPASS

   An instrument used to determine direction. It consists of a free moving magnetized needle that aligns North and South.

3. FERROMAGNETIC

   A material that becomes strongly magnetized when placed in a magnetic field.

4. HORSESHOE MAGNET

   A material, shaped in the form of a horseshoe, that attracts iron and steel.

5. LODESTONE

   Natural magnets found in the Magnesia area of Asia called "Lodestones" which means "Leading Stone." The stone is now called "Magnetite."

6. MAGNET

   A material that attracts iron and steel.

7. MAGNETIC FIELD PATTERN

   The shape or general outline of the invisible lines of force that surround the magnet.

8. MAGNETIC POLES

   The earth's magnetic lines of force flow out the magnetic SOUTH POLE, around the earth, and reenter at the NORTH POLE.

9. OSCILLOSCOPE

   An instrument used to make visible, electrical values of a varying voltage versus time. These electrical waveforms are displayed on the screen of a cathode ray tube (crt).

10. TEMPORARY MAGNET

    A material that loses its magnetism when the magnetizing force is removed.

Electromagnetism

INFO SHEET 2

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Describe the magnetic field that exists around a wire that is carrying a current.
2. Determine the direction of the magnetic field around a wire carrying a current using the Left Hand Rule.
3. Describe the construction of a coil.
4. Draw the schematic symbols for air core and iron core coils.
5. Determine the North (N) and South (S) poles of an electromagnet using the modified Left Hand Rule.
6. Define the following magnetic units:

   Magnetic Field Strength, Ø
   Magnetic Flux Density, B
   Magnetomotive Force, mmf
   Field Intensity, H
   Permeability, μ
   Reluctance, $\mathcal{R}$

7. Describe a magnetic circuit and relate it to an electrical circuit.
8. Perform magnetic circuit calculations using the magnetic "Ohm's Law."

DISCUSSION

Magnetism was described in Information Sheet 1 and the magnetic lines of force that formed the field surrounding the magnet were shown to be invisible to the human eye. It was also shown that the magnetic field affected other magnets and certain metals that came within the "field of influence."

MAGNETIC UNIT SYSTEMS

The magnetic field was represented by lines with arrowheads to show direction. The number of lines drawn indicated the strength of the magnetic field. In dealing with any

physical or scientific device or concept it is necessary to give numerical values to these forces. As an example, we can say that an object is "heavy," but we must say how heavy in numbers and units. The object can weigh 2 pounds or 50 ounces or even 3 1/2 tons. In your electrical and electronic experience you have specified electromotive force in terms of volts, resistance in ohms and current in amperes. Similarly it is necessary to specify magnetic circuit units and terms.

Magnetism is a highly specialized area of study and many of the terms to be introduced below will only occasionally be encountered by you in the field. They are, however, necessary to establish a good theoretical base in electrical and electronic study.

The three systems of notation were presented earlier as:

1. mks (meter-kilogram-seconds, also called SI units)

2. cgs (centimeter-grams-seconds)

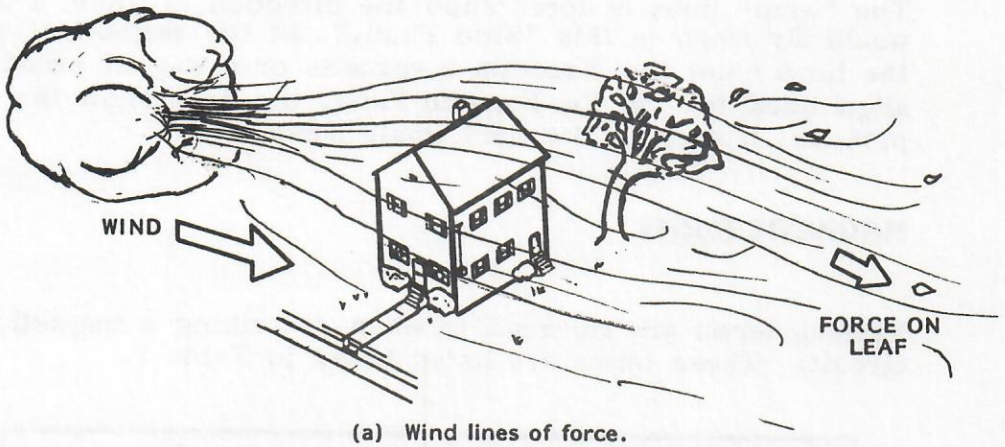
3. English (inches-pounds-seconds)

The conversions between all three systems are listed at the end of this information sheet. The mks system is the present standard and is preferred now in the literature and new text books.

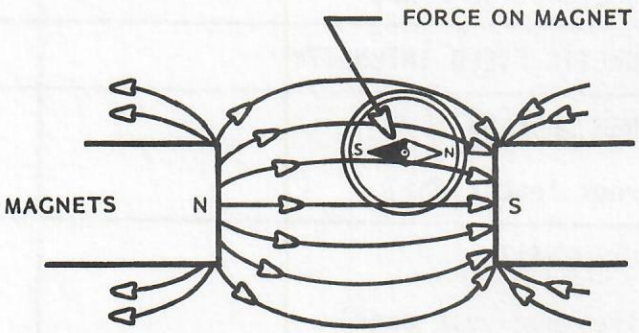
LINES OF FORCE

Consider the lines of force generated by three different sources shown in Figures 1(a), (b) and (c) on the next page. In each case the lines are not visible to the human eye.

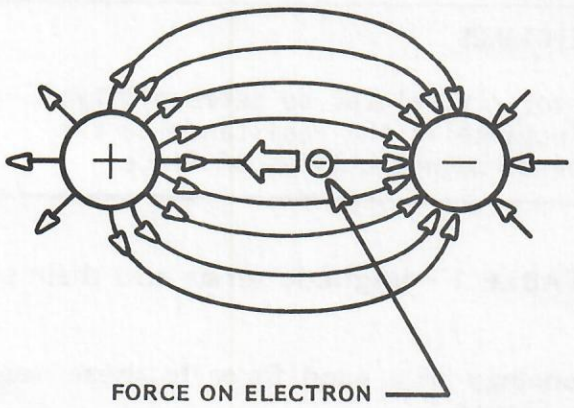
When the wind flows it is not visible. It can however be represented in a drawing by lines with arrows to indicate direction of flow. The more lines drawn in a given area, the stronger the wind that is indicated. The wind has to travel through and around various "materials;" air, trees, flowers, house, etc. The wind travels through air with relative ease, not halted much by flowers, slowed down quite a bit by trees and stopped almost completely by the house. Each of these materials has a certain relative ability to let the wind pass through. We might guess that if the air has a passage ability of 1000, the flowers might be 950, the trees 400 and the house 5 (leaks through doors, windows, etc.). Similarly, certain materials have different abilities to pass magnetic and electrical fields.



(a) Wind lines of force.



(b) Magnetic lines of force.



(c) Electrostatic lines of force.

Figure 1 - Lines of force.

The "wind" lines of force show the direction in which a leaf would fly when in this "Wind Field." In the Magnetic Field, the lines show the direction a compass or a magnet would align itself to. In the Electric Field, the lines show the path an electron in the field would move.

MAGNETIC TERMS

Various terms are referred to when describing a magnetic circuit. These terms are listed below in Table 1.

MAGNETIC TERM	SYMBOL
MAGNETOMOTIVE FORCE	mmf
MAGNETIC FIELD INTENSITY	H
LINES OF FLUX (Greek letter phi)	Ø
FLUX DENSITY (Lines per unit area)	B
PERMEABILITY (Ability to pass or concentrate flux) (Greek letter mu)	μ
RELUCTANCE (Inversely related to permeability; reluctance is the resistance to the flow of magnetic lines of force)	$\mathcal{R}$

TABLE 1 - Magnetic terms and their symbols.

A brief anology of a wind force to these magnetic terms is shown in Figure 2.

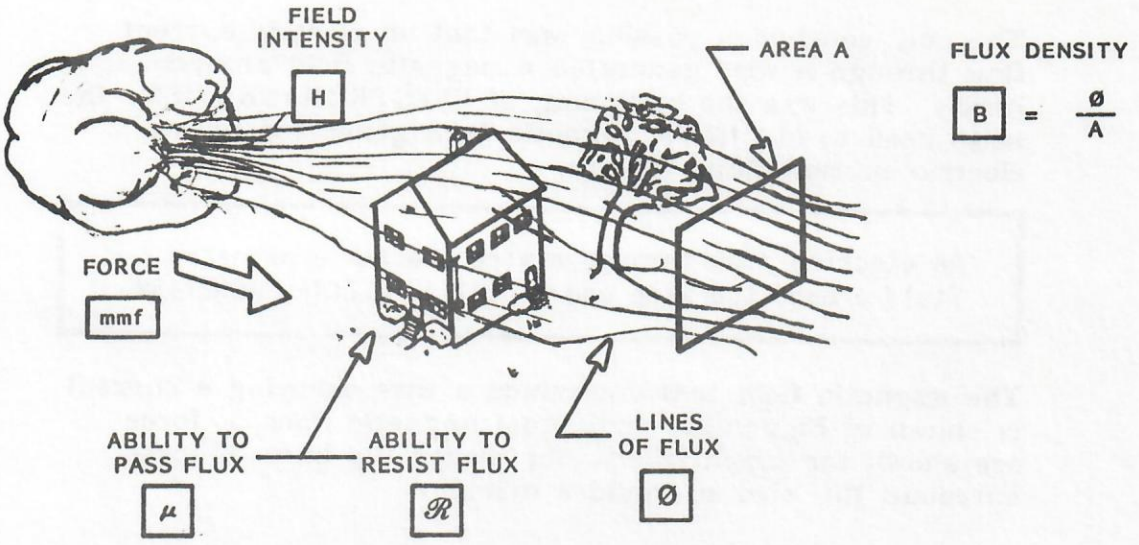


Figure 2 - Magnetic terms anology.

The Magnetomotive Force (mmf) is represented by the blower and represents the power or driving force behind the entire system. The magnetomotive force corresponds to voltage or electromotive force in an electrical circuit.

The Intensity of the field (H) is the strength of the magnetism and is inversely proportional to the distance over which it flows. It is comparable to a spreading wind.

The Lines of Flux (Ø) is the measurement of the magnetic field strength and depends upon the materials through which the field tries to flow. The Lines of Flux is comparable to the current flow in an electrical circuit.

The Flux Density (B) is a measurement of the lines of flux per a given unit area.

The Reluctance ($\mathcal{R}$) is equivalent to the resistance in an electrical circuit.

The Permeability (μ) is a measure of how well a material conducts magnetic lines of force.

ELECTROMAGNETISM

It was believed, for many years, that magnetism and electricity were unrelated. In 1819, however, a Danish physicist, Hans Oersted (1777-1851), observed that a compass needle was deflected when brought close to a wire carrying a current flow. Both the strength and direction of the current flow through the wire had an effect on the compass.

The only conclusion possible was that an electric current flow through a wire generated a magnetic field around itself. This was the beginning of ELECTROMAGNETISM, the name used to identify a magnetic field generated by an electric current flow. Thus:

> An electron flow through a wire creates a magnetic field around the wire and is called ELECTROMAGNETISM.

The magnetic field that surrounds a wire carrying a current is shown in Figure 3. Individual magnetic lines of force are shown for simplifiction. In reality the lines of force surround the wire as would a cylinder.

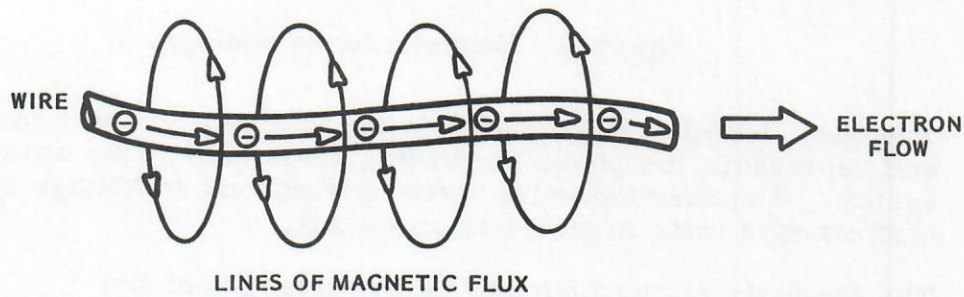


Figure 3 - Magnetic lines of flux that appear around a wire carrying an electric current.

MAGNETIC FIELD DIRECTION-LEFT HAND RULE

The direction of rotation of the magnetic field around a wire is determined by the direction of the current flow and that direction can be determined by applying the "Left Hand Rule." The left hand, as shown in Figure 4, is wrapped around the conductor with the thumb pointed in the direction of the electron flow. The curled fingers now point in the direction of the movement of the magnetic lines of force.

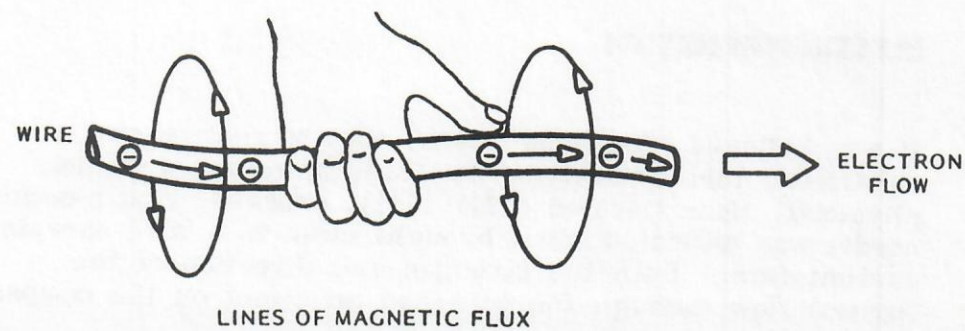


Figure 4 - Direction of flux lines determined by the Left Hand Rule for Electron Current.

Note that in Figure 4 the magnetic field around a single straight wire has no North or South pole, only a direction of flow of the lines of force in a closed loop.

LOOPS AND MAGNETIC FIELDS

The magnetic field around a straight wire has no polarity, is very weak and spread out over the entire length of the wire. By forming the wire into a single loop as shown in Figure 5, two very important changes take place. First, all the magnetic lines of force pass through the center of the loop, concentrating the lines of force. This results in a stronger field in the center of the loop. Second, all the lines of force flow through the center of the loop in the same direction (left hand rule). Since magnetic lines of force leave the North pole and enter at the South pole, it can be seen that the loop in Figure 5 produces a field that has a magnetic "polarity." The single loop, therefore, produces a magnetic field similar to that produced by a bar magnet but much weaker.

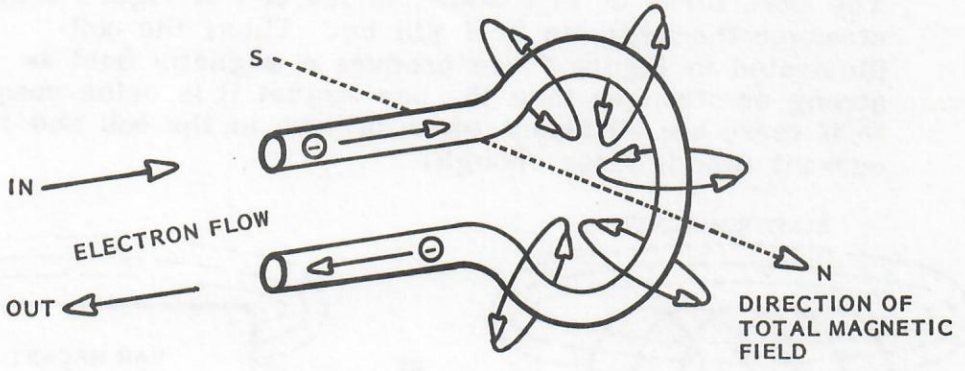


Figure 5 - Forming a conductor into a loop concentrates the magnetic field and polarizes it.

COILS

When a number of loops or COILS are formed, the magnetic field around each turn combines to concentrate the total field in the center of the coil as shown in Figure 6. The area inside the coil is called the CORE and can be air or some material with a greater permeability such as soft iron.

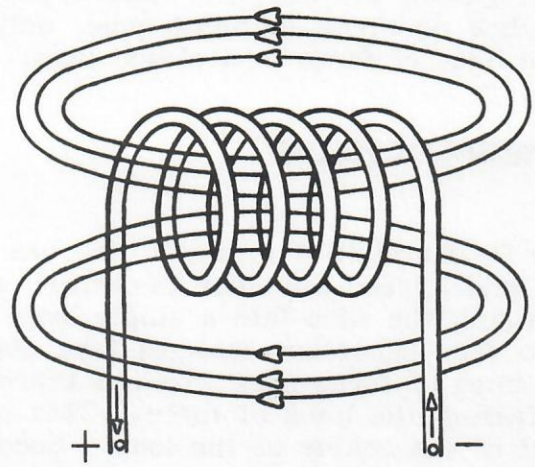


Figure 6 - Magnetic lines of force are created when a current flows through the coil and the lines of force are concentrated in the core area.

The more turns of wire added to the coil of Figure 6 the stronger the magnetic field will be. Thus, the coil illustrated in Figure 7 can produce a magnetic field as strong or stronger than the bar magnet it is being compared to if there are sufficient turns of wire in the coil and the current flow is large enough.

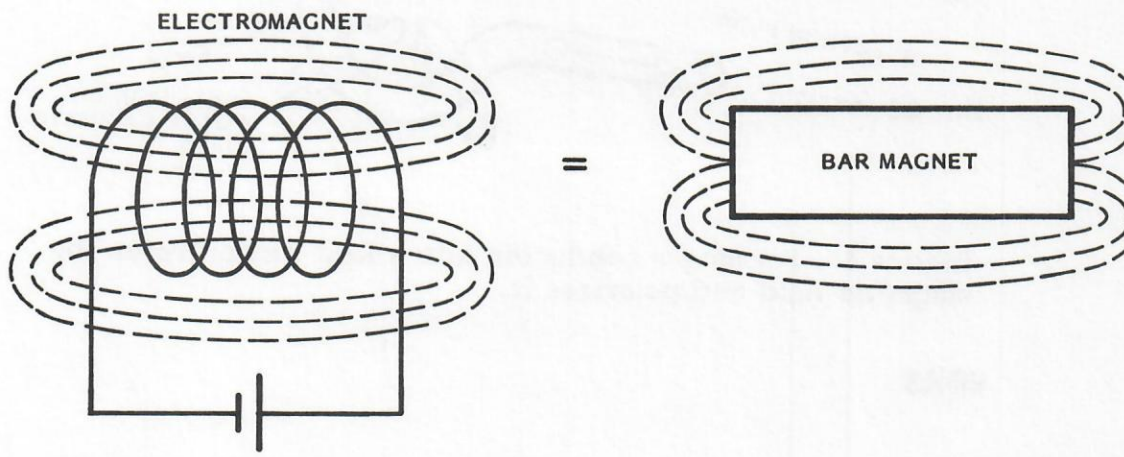


Figure 7 - A coil forming an electromagnet produces a field exactly like a permanent bar magnet.

CORES

It is possible to increase the strength of the field generated by an electromagnet by winding the coil on a soft iron core instead of just an "air core." The iron has a greater permeability (ability to pass magnetic lines) than air and so offers an easier path for the lines of force. An iron core coil and typical coil symbols are shown in Figure 8.

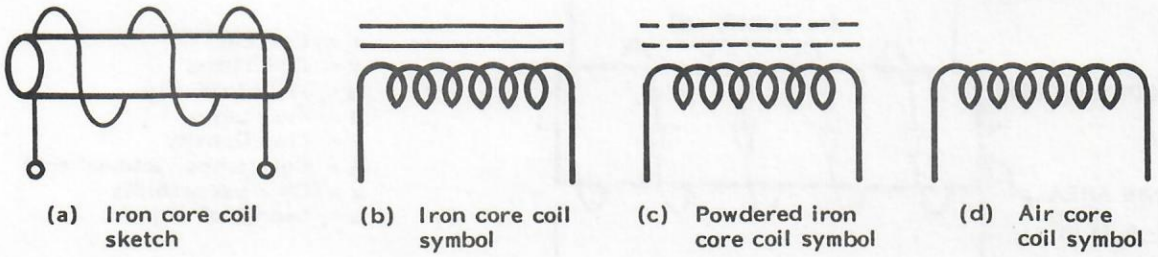


Figure 8(a) - Basic construction of an iron core coil. (b) - Symbol for an iron core coil. (c) - Powdered iron core coil symbol. (d) - Air core coil symbol.

LEFT HAND RULE FOR COILS

It is often necessary to determine the magnetic polarity of an electromagnet when trying to understand the operation of a motor or a similar magnetic device. To determine the magnetic polarity, the four fingers of the left hand are wrapped around the coil so that they point in the direction of electron flow (Figure 9). The thumb will now be pointing in the direction of the flow of magnetic lines of force through the core. Since lines of force leave the core of the coil at the North end, the thumb is pointing to the North pole of the magnet.

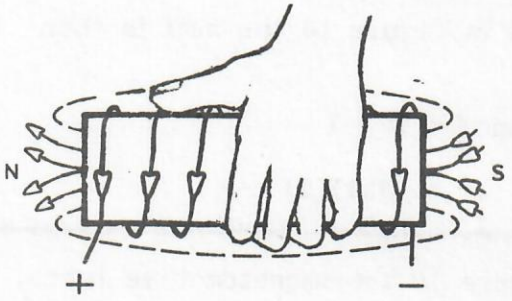
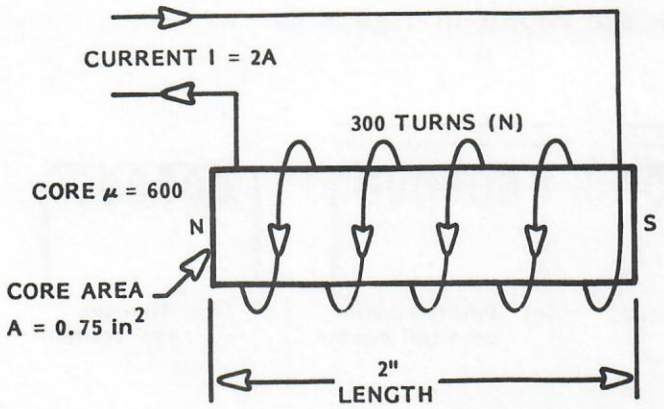


Figure 9 - The left hand rule applied to coils shows the fingers wrapped in the direction of electron flow and the thumb pointing to the North pole of the electromagnet. Used for Electron Flow current.

MAGNETOMOTIVE FORCE

Consider a coil of wire with a core material as shown in Figure 10.



I = Current
N = Coil Turns
H = Field Intensity
Ø = Flux Lines
B = Flux Density
A = Core cross sectional area
μ = Core permeability
L = Length of core

Figure 10 - A typical iron core coil, its characteristics and units of measurement.

First, using the Left Hand Rule for coils it can be determined that the flux lines flow through the core from right to left to create the magnetic poles shown.

The magnetomotive force developed is determined by the current and the number of turns. It is expressed as

$$mmf = N \cdot I$$

where mmf = magnetomotive force in Ampere Turns (AT).
N = number of turns in the coil.
I = the current flow in Amperes.

For the coil in Figure 10 the mmf is then

$$mmf = N \cdot I$$

$$= (300)(2)$$

For Figure 10 the magnetomotive force, mmf = 600 AT.

Note that in both the English and mks systems of measurement, mmf is measured in Ampere-Turns. In the cgs system, magnetomotive force is measured in the GILBERT. A Gilbert is equal to 1.257 Ampere-Turns (or Gilbert = $0.4\pi NI$).

FIELD INTENSITY (H)

The FIELD INTENSITY (H) developed by a coil depends upon the length of the coil (when the core is air) or the length of the core where the core is a good magnetic material. Assume that the coil and core are the same length as shown in Figure 10 and the Field Intensity (H) is determined by:

$$H = \frac{N I}{L}$$

where H = Field Intensity
NI = mmf
L = length of the coil core.

For the coil in Figure 10, we have:

$$H = \frac{N I}{L}$$

$$= \frac{(300)(2)}{2}$$

For Figure 10 the Field Intensity, H = 300 AT/INCH

In the English system H is in terms of AT/INCH as shown above. In the mks system H is in terms of AT/METER and in the cgs system it is in oersteds. An oersted is equal to (AT/M) times (79.6) and (AT/INCH) times (2.02). There are conversion tables on page 17.

PERMEABILITY (μ)

The permeability (μ) of a material was discussed earlier in Information Sheet 1 where it was noted that air has a μ of 1. Soft iron could have a μ of 600 which means that the core will produce a greater flux density than the same coil with an air core.

Note that in the cgs units, air has a μ defined as 1. In the mks and English system it has different values. For the illustration chosen in Figure 10, the core material, iron, has a μ in cgs of:

IN CGS SYSTEM	Iron Core Permeability, μ = 600

Permeability is discussed in more detail on page 18.

MAGNETIC FIELD STRENGTH (Ø)

The strength of the magnetic field developed by an electromagnet is measured by the number of lines of force. This is referred to as the MAGNETIC FLUX and its symbol is the Greek letter Ø (phi). This will be calculated later.

MAGNETIC FLUX DENSITY (B)

The FLUX DENSITY (B) is the number of magnetic lines of flux for a given cross sectional area of the electromagnet core. Flux Density, B, may be expressed as

$$B = \frac{\Phi}{A}$$

where B = Flux Density per unit area
Ø = Total magnetic flux
A = Cross sectional core area

This will be calculated for our example later. In the English system the area A is the cross sectional core area in in^2 and for mks it is the $meter^2$. In the cgs system, the area A is in cm^2.

MAGNETIC UNIT RELATIONSHIPS

When the field intensity (H) is specified, the actual flux density (B) that will be created depends upon the core material permeability, μ. The relationship between H, B and μ is given as:

$$\mu = \frac{B}{H}$$

The equation for μ transposes into

$$H = \frac{B}{\mu} \quad \text{and} \quad B = \mu H$$

Recall that for the coil in Figure 10, we have determined the following data

I = 2 Amperes
N = 300 turns
mmf = 600 AT as previously calculated
H = 300 AT/inch as previously calculated (ENGLISH SYSTEM)

CORE DATA
Length (L) = 2 inches
Area (A) = 0.75 in^2
μ = 600 (CGS SYSTEM)

To determine B, (LINES PER in^2 IN THE ENGLISH SYSTEM) we use

$$B = \mu H$$

$$= (600)(300)\left[\frac{(6.452)}{(2.02)}\right]$$

TO CONVERT μ IN CGS FOR USE IN ENGLISH SYSTEM, CONVERSION FACTORS FROM TABLE 4 ON PAGE 17 AND EXPLANATION ON PAGE 19

$$= (600)(300)\ (3.194)$$

For Figure 10 Flux Density, B = 574,930 lines per $inch^2$.

Note that flux density (B) in the ENGLISH system is LINES per $INCH^2$ as above; in the cgs system it is in Gauss and in the mks system it is in WEBERS per $METER^2$ also called TESLAS (T).

MAGNETIC FLUX (Ø)

If the core cross sectional area is 0.75 in^2 it is possible to determine the magnetic flux from the formula given earlier.

$$B = \frac{\text{Ø}}{A} \qquad \text{Transposing} \qquad \text{Ø} = BA$$

Given that A = 0.75 in^2 and B = 574,930 lines/in^2

$$\emptyset = (574,930)(.75) \text{ lines}$$

For Figure 10, Magnetic Flux, $\emptyset$ = 431,197 lines

ENGLISH SYSTEM

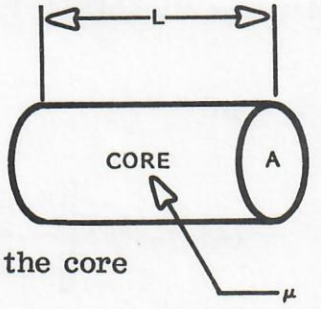
Note that the flux, $\emptyset$, in cgs is in MAXWELLS and in mks it is in WEBERS. Conversions are given on page 17.

RELUCTANCE ($\mathcal{R}$) USING PHYSICAL VALUES (METHOD 1)

RELUCTANCE ($\mathcal{R}$) is the resistance or opposition a material offers to the flow of magnetic lines of force. Reluctance is the opposite of permeability and a material with a high permeability has a low reluctance and a low permeability material has a high reluctance.

The reluctance of a material also varies with the length and cross sectional area and can be expressed as

$$\mathcal{R} = \frac{L}{\mu A}$$



where $\mathcal{R}$ = Reluctance
L = Length of Core
A = Cross sectional area of the core
μ = Permeability

Calculating the core reluctance using the permeability and core dimensions given earlier, we have:

$$\mathcal{R} = \frac{L}{\mu A}$$

where L = 2 inches
μ = 600
A = 0.75 in^2

$$\mathcal{R} = \frac{(2)}{(600)(0.75)} \left[\frac{(2.02)}{(6.452)}\right]$$

← CONVERSION FACTORS FROM TABLE 4 ON PAGE 17

$$= \frac{4.04}{2903.4}$$

Core Reluctance, $\mathcal{R}$ = 0.00139 AT/Line

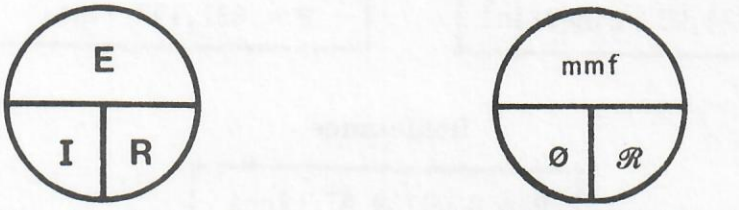
MAGNETIC CIRCUIT OHM'S LAW

It is possible to develop a magnetic equivalent of Ohm's Law based on the following relationships shown in Table 2.

ELECTRICAL UNIT	MAGNETIC EQUIVALENT
VOLTAGE	mmf
CURRENT	FIELD STRENGTH, Ø
RESISTANCE	RELUCTANCE, $\mathcal{R}$

TABLE 2 - Relationship between electrical and magnetic Ohm's Law.

These relationships can be expressed mathematically as shown in Figure 11.



(a) Electrical Ohm's Law (b) Magnetic Ohm's Law

Figure 11 - Electrical and Magnetic Ohm's Law.

RELUCTANCE ($\mathcal{R}$) USING MAGNETIC OHM'S LAW (METHOD 2)

It is now possible to calculate the reluctance using the above given magnetic Ohm's Law as follows:

$$\text{Ø} = \frac{\text{mmf}}{\mathcal{R}}$$

Transposing, we have

$$\mathcal{R} = \frac{\text{mmf}}{\text{Ø}}$$

Substituting values

$$\mathcal{R} = \frac{600 \text{ AT}}{431{,}197 \text{ lines}}$$

Core Reluctance, $\mathcal{R}$ = 0.00139 AT/Line

Observe that this is the same value obtained when using the physical formula for reluctance.

COIL SUMMARY DATA

For the coil in Figure 10, the resultant calculated magnetic values are:

Magnetomotive Force

mmf = 600 Amp-turns

Field Intensity

H = 300 AT/INCH

Flux Density

$B = 574{,}930$ Lines/in^2

Flux

$\theta = 431{,}197$ lines

Reluctance

R = 0.00139 AT/Lines

SUMMARY OF UNITS: ENGLISH, CGS, MKS (SI)

The terms used for all three systems of measurement are summarized in Table 3 on the next page.

The preferred standard in use today in scientific work is the mks or SI system.

Mks is meter-kilogram-seconds.

SI stands for Systeme International d'Unit'es.

UNIT	SYMBOL	ENGLISH	CGS	MKS (SI)
MAGNETIC FLUX	Ø	LINES OF FORCE	MAXWELL	WEBER
MAGNETOMOTIVE FORCE	mmf	AMPERE-TURN	GILBERT	AMPERE-TURN
FLUX DENSITY	B	$\frac{\text{Lines}}{\text{in}^2}$	GAUSS	$\frac{\text{WEBER}}{\text{METER}^2}$ Also called TESLAS (T)
FIELD INTENSITY	H	$\frac{\text{AT}}{\text{inch}}$	OERSTED	$\frac{\text{AT}}{\text{METER}}$

TABLE 3 - Magnetic terms used in each of the unit systems.

Also shown, in Table 4, are the mathematical relationships between the units and their conversion factors.

TERM	FROM	TO	MULTIPLY BY	CONVERSELY
mmf	AT	GILBERTS	1.257	0.7958
B	AT/in^2	$AT/METER^2$	0.155	6.452
B	$WEBERS/METER^2$	GAUSSES	10^4	10^{-4}
B	GAUSSES	TESLAS	10^{-4}	10^4
B	GAUSSES	$LINES/METER^2$	6.452	0.155
H	AT/in	AT/cm	0.3937	2.54
H	AT/m	OERSTEDS	0.01257	79.577
H	AT/in	OERSTEDS	0.495	2.02
Ø	MAXWELLS	WEBERS	10^{-8}	10^8
Ø	LINES OF FORCE	MAXWELLS	1	1

TABLE 4 - Conversion factors for magnetic units.

PERMEABILITY (μ) MORE DATA

In a number of previous calculations where μ was used, it was necessary to use some of the conversion factors listed in Table 4. This is because the permeability, μ, of air is 1. The μ of 600 for the iron was in the cgs system and our calculations were in the English system. This note on permeability of magnetic materials is now given with more details.

In the cgs system, permeability, μ, is defined as 1 for air (or in a vacuum). Each material has a permeability value given relative to the cgs system for air and is expressed as

$$\mu = \frac{\text{number of flux lines per unit area in the core material}}{\text{number of flux lines per unit area in an air core}}$$

This is often called μ_r, the relative permeability. For the cgs system, $\mu = \mu_r$. Some typical permeability values are given in Table 5.

The mks system is the preferred standard in use today. The μ for air in mks is μ_o and can be shown to be $\mu_o = 0.4\pi \times 10^{-6}$. To use μ in the mks system we use the equation $\mu_r = \mu_o$.

MATERIAL	PERMEABILITY (μ_r)
Supermalloy	1,000,000
Permalloy	100,000
Iron	7,000
Nickel	1,000
Cobalt	170
Aluminum	1.0000214
Air	1.0000004
Vacuum	1.0000000
Copper	0.999995
Quartz	0.000085
Water	0.000001

TABLE 5 - Permeability ratings of some materials compared to air which is considered to have a μ of 1 for all practical purposes.

DIMENSIONS OF (μ)

The definition of μ was given as:

$$\mu = \frac{B}{H}$$

If B and H are in the cgs system as gauss and oersted respectively, the u has the dimensions of

$$\mu = \text{gauss/oersted} \qquad \text{(in cgs)}$$

If B and H are in the English system as Lines/in^2 and AT/in respectively, then μ has the dimensions of

$$\mu = \text{Lines/AT-in} \qquad \text{(in English)}$$

Our given values in the example of Figure 10 was with μ of 600 (cgs system) which we have to convert to the English system by multiplying by the proper factor which must have the dimensions of:

$$\frac{\text{Lines}}{\text{AT/IN}} \times \frac{\text{Oersted}}{\text{Gauss}} \qquad \text{(Conversion dimensions)}$$

Looking in Table 4, these factors are:

$$\frac{\text{Oersted}}{2.02 \quad \text{AT/IN}} \qquad \frac{6.452 \text{ LINES/IN}^2}{\text{Gauss}} = \frac{6.452}{2.02}$$

This above factor was used to solve for B on page 13 as necessary to convert μ = 300 from cgs to English.

SCIENTISTS AND UNITS

The development of the magnetic theory presented above was over a period of hundreds of years. To honor the many scientists involved in this development, the various magnetic units have been named after them. These are:

William Gilbert (1544-1603) an English physician and physicist. (gilbert, Gb)

Karl Gauss (1777-1855) a German mathematician. (gausses, g)

Hans Oersted (1787-1854) a Danish physicist. (oersteds, oe)

Wilhem Weber (1804-1891) a German physicist. (webers, w)

James Maxwell (1831-1879) a Scottish physicist. (maxwell, m)

Nikola Tesla (1857-1943) an American physicist. (teslas, T)

THE B-H RELATIONSHIP

As the current flow through an air core coil is increased, the magnetizing force, H (equal to NI/L) increases. This increases the flux density, B (lines per square inch in the coil core). If, for an air core coil, H is doubled, B will also double.

When a soft iron core is added to the coil, the relationship between B and H changes. As H is strengthened by increasing the current, more and more of the core's molecular magnets fall into alignment. As H is increased further it becomes more difficult to align the remaining molecular magnets and the lines of force in the core do not increase as rapidly. This results in a non-linear relationship between B and H. Finally, when all of the molecular magnets of the core are aligned, any further increase in current flow or H produces no further increase in B, the lines per square inch in the core. This condition is called SATURATION, where an increase in H results in no further increase in B.

This relationship between B and H (called the B-H curve) will be studied in more detail in Part G3 - Experiment No. 5, THE B-H CURVE, where the curve will be observed and other factors such as Rententivity and Coercivity will be described.

CONCLUSIONS

We have learned from this information sheet that:

Magnetic quantities can be expressed in three different systems, English, cgs and MKS (or SI). MKS (SI) is the standard.

Magnetic units of measurement are:

Magnetomotive force - mmf	Lines of force Ø
Magnetic field intensity - H	Flux density - B
Permeability - μ	Reluctance - $\mathcal{R}$

When a current flows through a wire, a magnetic field is generated.

Forming the wire into a coil increases the electromagnetic field strength and creates a field pattern like that of a bar magnet.

Adding a core of some ferromagnetic substance (typically soft iron) to an electromagnet increases the field strength.

The magnetic polarity of an electromagnet can be determined using the left hand rule for coils.

Reversing the direction of current flow through an electromagnet reverses the magnetic polarities.

Magnetomotive force is equal to the number of turns on the coil multiplied by the current in amperes. (mmf = NI) This corresponds to voltage in an electrical circuit.

Field intensity of an electromagnet (H) is equal to NI/L.

Permeability of a core material, μ, is the measurement of the core material's ability to conduct magnetic lines of force.

Magnetic field strength (Ø) is the total number of magnetic lines of force and corresponds to the current in an electrical circuit.

Magnetic flux density (B) is the number of lines of flux per a unit of cross sectional core area in in^2, cm^2 or m^2.

Reluctance ($\mathcal{R}$) is the opposition to flow of magnetic lines in a material. This corresponds to resistance in an electrical circuit.

The following magnetic relationships exist:

$$\mu = \frac{B}{H} \qquad H = \frac{B}{\mu} \qquad B = \mu H$$

$$B = \frac{\Phi}{A} \qquad A = \frac{\Phi}{B} \qquad \Phi = BA$$

$$\mathcal{R} = \frac{L}{\mu A} \qquad \mathcal{R} = \frac{mmf}{\Phi}$$

$$mmf = \Phi\mathcal{R} \qquad \Phi = \frac{mmf}{\mathcal{R}}$$

ASSIGNMENT

Answer the following True-False questions.

1. A current flowing through a wire creates a magnetic field with a N pole at the end of the wire that is connected to the negative terminal. ____

2. The strength of a magnetic field around a wire is directly proportional to the current flow. ____

3. The direction of the magnetic field around a wire can be determined using the left hand rule. ____

4. A wire formed into a coil will produce a magnetic field strength that is inversely proportional to the number of turns. ____

5. An electron has a magnetic field about it when in motion. ____

6. A soft iron core added to an air core coil increases the number of lines of force in the core area. ____

7. When the left hand rule is applied to coils the thumb points to the S pole. ____

8. The symbol for magnetic field strength is B. ____

9. The symbol for magnetic flux density is H. ____

10. The magnetic flux density is measured in the core cross sectional area of in^2 or cm^2 or m^2. ____

11. Magnetomotive force, mmf, is the magnetic equivalent of voltage in an electrical circuit. ____

12. Given an mmf of 500 and 200 turns, the current flow in the coil is equal to 40 mA. ____

13. A magnetic field developed by a coil of 500 T and 2A has the same strength as a field developed by a 250 T winding with a 4A flow. ____

14. A magnet that develops 500 AT over a length of 2" has a higher field intensity than one that develops 500 AT over a 1" length. ____

15. The mu of air is approximately 1. ____

16. Permeability, μ, can be computed from H/B. ____

17. Permeability is defined as the measure of ease with which a material conducts magnetic lines of force. ____

18. Reluctance is symbolized by $\mathcal{R}$ and is the opposite of permeability. ____

19. Magnetic Ohm's Law states that mmf = $\emptyset/\mathcal{R}$. ____

20. A magnetic core that has high reluctance has a low permeability. ____

21. Draw the circuit symbols for the following coils:
    a. air core
    b. iron core
    c. powdered iron core

KEY TERMS

1. AMPERE-TURNS

   The magnetomotive force (mmf) generated by a coil when current flows through it. The mmf = NI = AT. The equivalent of voltage in an electrical circuit.

2. COIL

   Turns of wire wound around a form or core.

3. ELECTROMAGNET

   A temporary magnet made from a coil of wire wound on a soft iron core.

4. FIELD INTENSITY (H)

   The amount of magnetic lines of force produced by a magnet per unit length.

5. FLUX (Ø)

   Magnetic lines of force in a magnetic circuit. Flux is the equivalent of current flow in an electrical circuit.

6. FLUX DENSITY (B)

   The amount of flux per unit area ($inch^2$; cm^2 ; m^2).

7. GAUSS

   The unit of flux density in cgs units.

8. GILBERT

   The unit of magnetomotive force in cgs units.

9. LEFT HAND RULE

   A rule stating that when the fingers of the left hand are wrapped around the wire so that the fingers point in the direction of electron flow, the extended thumb will be parallel to the flow of magnetic lines of force with the thumb pointing north.

10. MAGNETIC FIELD

    Area around a magnet where lines of force exist.

11. MAGNETOMOTIVE FORCE

    See Ampere-Turns.

12. MAXWELL

The cgs unit of Magnetic Flux (Ø).

13. OERSTED

The cgs unit of Magnetizing Force (H).

14. PERMEABILITY (μ)

The measure of how much better a material conducts magnetic lines of force compared to air.

15. RELUCTANCE ($\mathcal{R}$)

The opposite of permeability; a measure of the opposition to the flow of magnetic flux. The magnetic equivalent of electrical resistance.

16. TESLA

The unit of magnetic flux density (B) in the mks units. It is equal to 1 Weber/meter^2 , also a mks unit.

17. WEBER

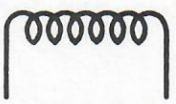
The mks unit of magnetic flux. One Weber equals 10^8 lines of force.

18. WEBER/METER^2

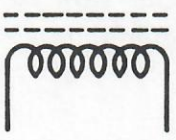
The msk unit of magnetic flux density.

CIRCUIT SYMBOLS

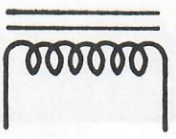
1. AIR CORE COIL



2. IRON CORE COIL



3. POWDERED IRON CORE COIL



Electromagnets 2

OBJECTIVES

When you finish this experiment, you will be able to:

1. Detect the presence of a magnetic field around a wire carrying a current.
2. Verify the relationship between current level and magnetic field strength.
3. Verify the relationship between current direction and magnetic polarity.
4. Wind an air core coil and use it to estimate the Earth's magnetic field strength.
5. Wind an electromagnet and calculate the magnetomotive force it generates.
6. Use an electromagnet to lift ferromagnetic materials (iron, etc.).

DEMONSTRATION

This experiment uses two external coils. These coils may be pre-wound and used by the instructor for demonstration rather than have the experiment performed by the students.

ADDITIONAL EQUIPMENT

Part 1 - Air Core Coil (Experiment or Demonstration)

a. Pre-assembled coil of wire with 57 turns or a 30 foot length of No. 22 insulated hookup wire.

b. Magnetic Compass

c. 2 Banana to Alligator clip adapters (Optional)

Part 2 - Iron Core Coil (Experiment or Demonstration)

a. Pre-assembled coil of 300 turns of No. 24 enameled wire on a 20 d nail or a spool of No. 24 wire and the 20 d nail.

b. 2 Banana to Alligator clip adapters (Optional)

c. Paper Clip; Standard size (1 1/4")

d. 2 D size cells and holder (Optional)

DESCRIPTION

The concepts and principles of electromagnets were discussed in Information Sheet 2, Electromagnetism. A current flowing through a coil of wire creates a magnetic field inside the coil and around the outside as well.

In this experiment we will use two coils of wire to produce magnetic fields as shown in Figure 1.

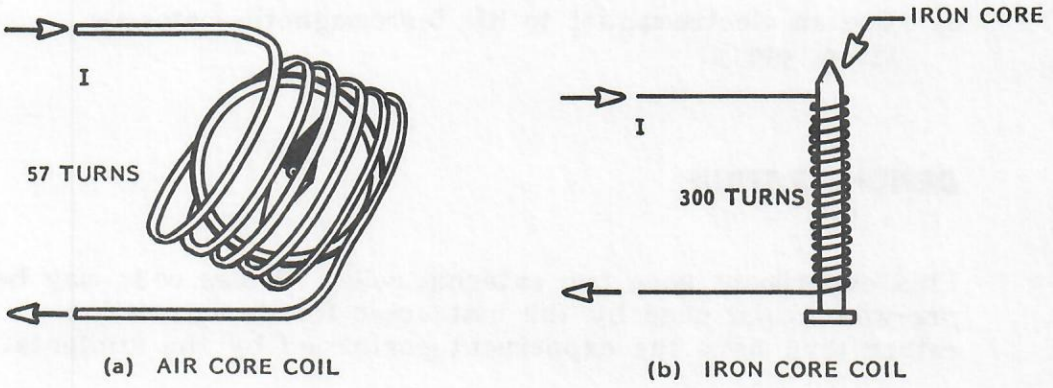


Figure 1 - Two coils used in the electromagnetic experiments.

AIR CORE COIL ASSEMBLY (Figure 1a)

The first part of the procedure establishes the presence of a magnetic field around a wire. In order to strengthen the field so that it can be detected by the compass, between 55 to 60 turns of wire are wrapped to form a coil as shown in Figure 1(a). It is now possible to observe the effect of current direction and strength on the magnetic field by observing the direction and amount of movement of the compass pointer.

IRON CORE COIL ELECTROMAGNETIC ASSEMBLY (Figure 1b)

The second part of the procedure outlines the construction of a very simple electromagnet. It is first powered from the Ed-Lab trainer with a limited maximum current and so does not produce a strong magnetic field. The electromagnet can be powered from two D cells if they are available. The D cells are often called batteries but the precise definition of a battery is the combination of two or more cells. The increased current of approximately 800 mA to 1 Ampere, can be drawn for a very short period of time only. The electromagnet winding has a very low resistance and acts as a short circuit across the battery. The use of the D cells will result in a great increase in magnetic field strength.

PROCEDURE

2.1 MAGNETIC FIELD, AIR CORE COIL

1. You may have to wind a coil or you may use a coil that has already been assembled.

   If you are to wind the coil, use a 30 foot length of No. 22 insulated hookup wire or you may prefer to wind directly from a large roll of wire.

   Wind between 55 to 60 turns around a form that will be just large enough to allow the compass to be placed in the coil center. You may use three of your fingers in parallel as the form around which to wind the coil. Do not make the coil too tight or you will not be able to remove the coil from your fingers. Keep the coil windings as close together as possible so that it is 1" to 1 1/2" wide as shown in Figure 2.

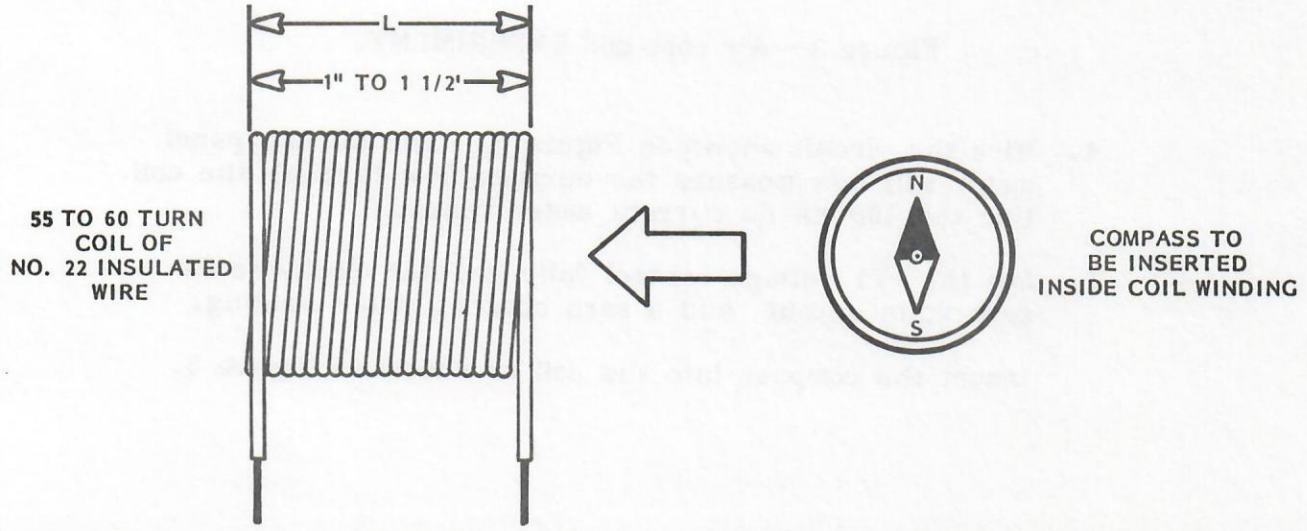


Figure 2 - Air core coil construction and compass location; EXPERIMENT.

2. Record the number of coil turns below

N = _____ turns

Measure and record the length (L in Figure 2) of the coil below.

L = _____ inches

3. Strip the ends of the coil wires as shown in Figure 2. It will be helpful to use a small piece of tape to hold the coil together.

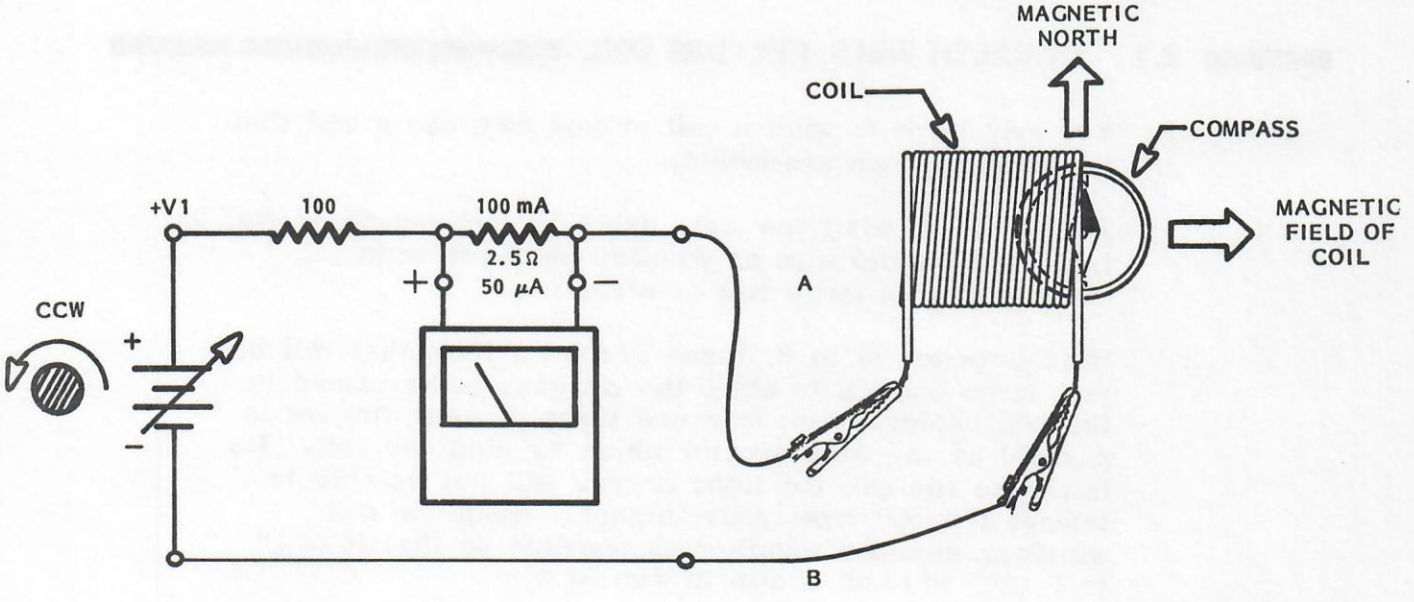


Figure 3 - Air core coil EXPERIMENT.

4. Wire the circuit shown in Figure 3. The Ed-Lab panel meter will now measure the current flow through the coil. Use the 100 mA dc current meter range.

5. Set the +V1 voltage control fully counter clockwise for zero volts output and a zero current meter reading.

Insert the compass into the coil as shown in Figure 3.

6. Hold the compass and coil assembly level and rotate it until the compass needle points to magnetic North as shown in Figure 3. This places the coil field, when it appears, at right angles or perpendicular to magnetic North as shown in Figure 3.

7. Rotate the +V1 voltage control knob fully clockwise.

   What happens to the compass needle direction? _____

   _____

   _____

   _____

   Reverse the polarity of the voltage connected to the coil by switching alligator clips A and B.

   What effect does this change of polarity have on the compass pointer direction? _____

   _____

   _____

   _____

8. Read the current flow in the coil from 0-10 scale, multiply that reading by 10, and record it below.

   I_{COIL} = _____ A

9. Calculate the Magnetomotive Force (mmf) developed by the electromagnet. Recall that it is equal to

   $$mmf = N \cdot I$$

   where I = coil current in Amperes

   N = the number of turns on the coil

   mmf = ( ) ( )

   mmf = _____ ampere turns

10. Calculate the Field Intensity (H) in the center of the coil. The longer the coil length (L) the less the intensity. The equation is:

$$H = \frac{N \cdot I}{L} = \frac{mmf}{L}$$

where L is in inches from step 2 and the mmf in AT is taken from step 9.

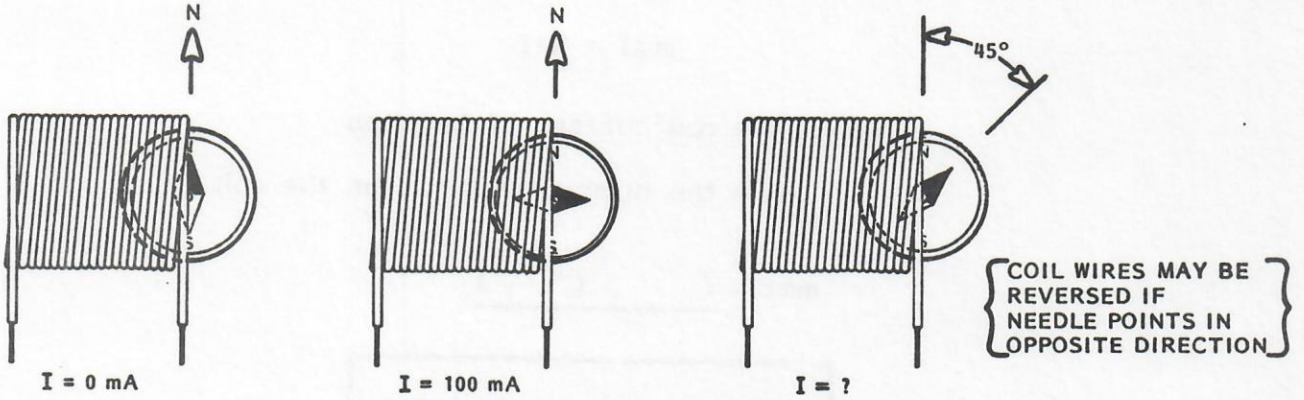
$$H = \frac{(\quad)}{(\quad)}$$

$$H = \frac{AT}{INCH}$$

2.2 EARTH'S MAGNETIC FIELD

11. The earth's magnetic field directs the compass needle in Figure 4a below, when there is no current flow through the coil. If the magnetic field of the coil is much greater than that of the earth the compass needle will point in the direction of the axis of the coil as shown in Figure 4 (b).

When both field strengths are equal, the compass needle will be mid-way between the two positions or at 45 degrees as shown in Figure 4(c).



(a) Earth's magnetic field only.

(b) Very strong coil magnetic field

(c) Coil field equals earth's field.

Figure 4 - Compass as affected by Earth and coil fields; EXPERIMENT.

12. Set the coil current to zero by rotating the voltage control knob counter clockwise.

13. Hold the coil-compass assembly in your hand in a stable position so that the compass needle points North and parallels the coil as shown in Figure 4(a) and is free to rotate.

14. Increase the +V1 voltage control until the pointer has rotated 45 degrees as shown in Figure 4(c). (NOTE: The coil is still wired into the circuit of Figure 3.)

    Read and record the current flow through the coil. (Recall that you are on the 100 mA scale.)

CURRENT TO EQUAL EARTH'S MAGNETIC FIELD	I_{earth} = _____ A

15. Calculate the Field Intensity (A) as before, using I_{earth} from step 14 above.

    This Field Intensity is approximately equal to the earth's field. Use I in Amperes and L in inches.

$$H = \frac{N \cdot I}{L}$$

$$H = \frac{(\quad)(\quad)}{(\quad)}$$

MEASURED EARTH'S MAGNETIC FIELD INTENSITY	H = _____ $\frac{AT}{INCH}$

16. Field Intensity H (and other magnetic terms) can be expressed in one of three systems of measurement as shown below and listed earlier in Information Sheet 2.

	ENGLISH	cgs	mks
H	$\frac{AMP\text{-}TURNS}{INCH}$	OERSTEDS	$\frac{AMP\text{-}TURNS}{METER}$

To convert from the English AT/in to the cgs dimension of Oersteds, it is necessary to multiply AT/in by 0.495.

Calculate the strength of the Earth's magnetic field, in oersteds, at your location, based on the Field Intensity, $H_{AT/IN}$, calculated in step 15.

$$H_{oe} = (H_{AT/IN})(0.495)$$

$$= (\quad)(0.495)$$

MEASURED EARTH'S MAGNETIC FIELD INTENSITY	H_{oe} = _____ oersteds

17. Using a text reference to determine the Earth's magnetic field strength in oersteds, we find in "Systems Engineering Handbook" by R.E. Machol, published by McGraw Hill, Chapter 3, page 6, that the area of least intensity (less than 0.25 oersted) is in eastern Brazil while the areas of greatest intensity are the two poles the South Pole being 0.70 oersteds.

An average field strength can be determined from the highest and lowest values as:

$$H_{oe\ av} = \frac{(H_{low}) + (H_{high})}{2}$$

$$\frac{0.25 + 0.7}{2}$$

$$H_{oe\ av} = 0.475 \text{ oersteds}$$

This should be on the same order as your calculated value in step 16. How does the calculated field strength compare?

_____

_____

_____

This concludes the testing using the air core coil.

2.3 ELECTROMAGNETIC CONSTRUCTION (OPTIONAL)

18. Use a pre-assembled electromagnet or prepare one as shown below.

    Wind 300 turns of the No. 24 enameled wire using a 20 penny nail as the soft iron core as shown in Figure 5 below.

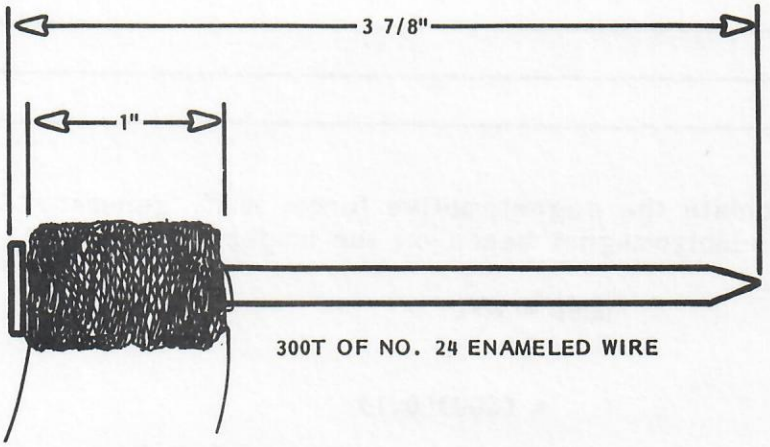


Figure 5 - Construction of an electromagnet; EXPERIMENT.

19. Connect the electromagnet in the circuit as shown in Figure 6 first scraping off the enamel to allow good connection.

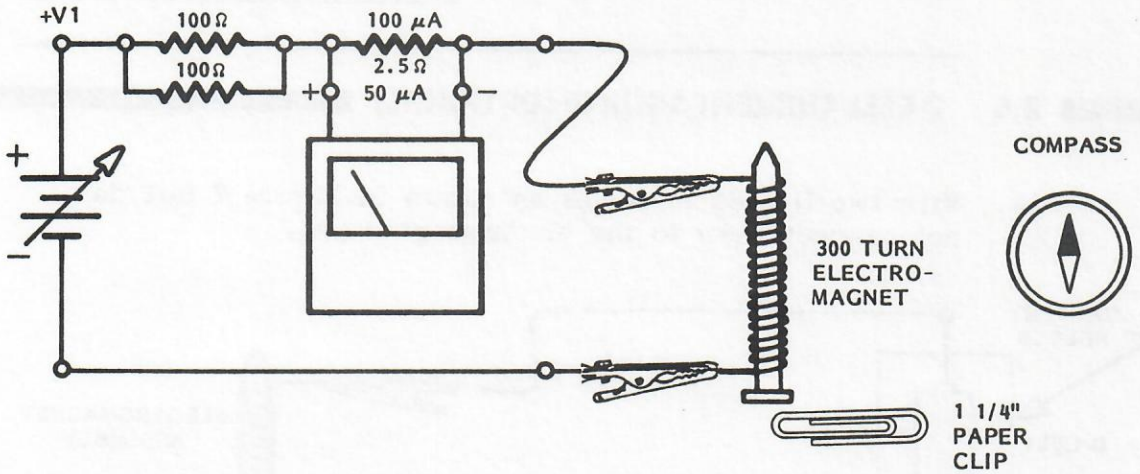


Figure 6 - Electromagnet connected to the +V1 voltage source; EXPERIMENT.

20. Apply power and adjust +V1 for a 100 mA reading on the milliammeter.

21. Bring one end of the electromagnet close to the compass pointer and observe the pointer behavior.

    Reverse the eletromagnet and bring the opposite end close to the compass and observe the pointer behavior.

    Describe the behavior of the compass pointer for each action above. _____

    _____

    _____

    _____

22. Calculate the magnetomotive force, mmf, generated by the electromagnet based on the ampere turns.

    $$mmf = N \cdot I$$

    $$= (300)(0.1)$$

    mmf = _____ Ampere Turns

    Pick up a small paper clip with the electromagnet.

    Does the electromagnet exhibit a weak or strong field when picking up the paper clip. _____

    _____

2.4 D CELL CURRENT SOURCE (OPTIONAL)

23. Wire two D cells in series as shown in Figure 7 but do not connect them to the electromagnet yet.

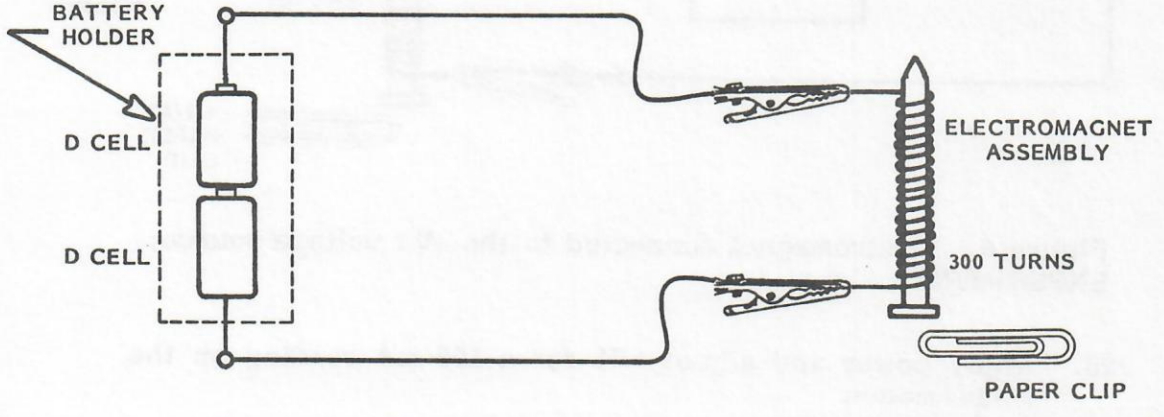


Figure 7 - Electromagnet connected across two series D cells; EXPERIMENT.

24. Connect the electromagnet wires to the D cells for no longer then several seconds and pick up the paper clip with the electromagnet.

    Is the electromagnet more powerful than before? _____

    Explain why. _____

    _____

    _____

25. Determine the magnetomotive force developed by the electromagnet assuming a battery current of 900 mA (0.9 A).

$$mmf = N \cdot I$$

$$= (300)(0.9)$$

MAGNETOMOTIVE FORCE WITH D CELLS	mmf = _____ AT

CONCLUSIONS

We have learned from this experiment that:

A magnetic field exists around a wire carrying current.

The direction of the current flow through the wire determines the direction of the magnetic field around the wire.

The strength of the magnetic field around a wire is directly proportional to the current flow.

The magnetic field strength around a wire is strengthened by winding the wire into a coil.

The greater the number of turns in the coil the stronger the magnetic field.

The magnetic field formed by a coil with a current flowing through it has a N and S pole.

ASSIGNMENT

Answer the following True-False questions.

1. A current flowing through a single wire creates a magnetic field in the center only, not at the ends of the wire. _____

2. Forming the wire into a coil strengthens the magnetic field but does not change the field in any other way. _____

3. The strength of the magnetic field around the coil is inversely proportional to the current flowing through it. _____

4. Reversing the direction of the current flow through an electromagnet reverses the direction of the magnetic field. _____

5. The magnetic field strength of an air core coil can be increased by the addition of an iron core. _____

KEY TERMS

1. AMPERE TURNS

   The product of the number of coil turns and the current, in amperes, flowing through the coil. The unit of measurement is magnetomotive force, mmf. mmf = A x T.

2. COIL

   Turns of wire wound around a form or core.

3. CGS UNITS

   A system of scientific notation based centimeters, grams and seconds.

4. CORE

   The material in the center of a coil. The coil core may be air or a form of iron or a similar magnetic material.

5. ENGLISH UNITS

   A system of notation based on inches, pounds and seconds.

6. FIELD INTENSITY (H)

   The amount of magnetic lines of force produced by a magnet per unit length. It is expressed as H = AT/LENGTH.

7. MKS UNITS

   A system of scientific notation based on meters, kilograms and seconds. Also known as SI Units.

Relays

3

OBJECTIVES

When you finish this experiment. you will be able to:

1. Explain the operation of a relay.
2. Draw relay symbols with a variety of switching contacts.
3. Use the CES 318 Relay Module.
4. Determine the minimum pull-in voltage of a relay coil.
5. Determine the drop-out voltage of a relay coil.
6. Wire the relay into a lamp control circuit.
7. Wire the relay into a buzzer circuit.

ADDITIONAL EQUIPMENT

1 - CES 318 Relay Module or equal

DESCRIPTION

As stated earlier, magnetism and electromagnetism are used to operate many devices involved in electronic circuits. One of the most popular devices is called a RELAY.

RELAY

A relay is a switch that is not operated by hand, but is instead operated by an electromagnet.

The relay has two basic parts, the electromagnet which produces the force, and the switch. The symbol for a relay is shown in Figure 1.

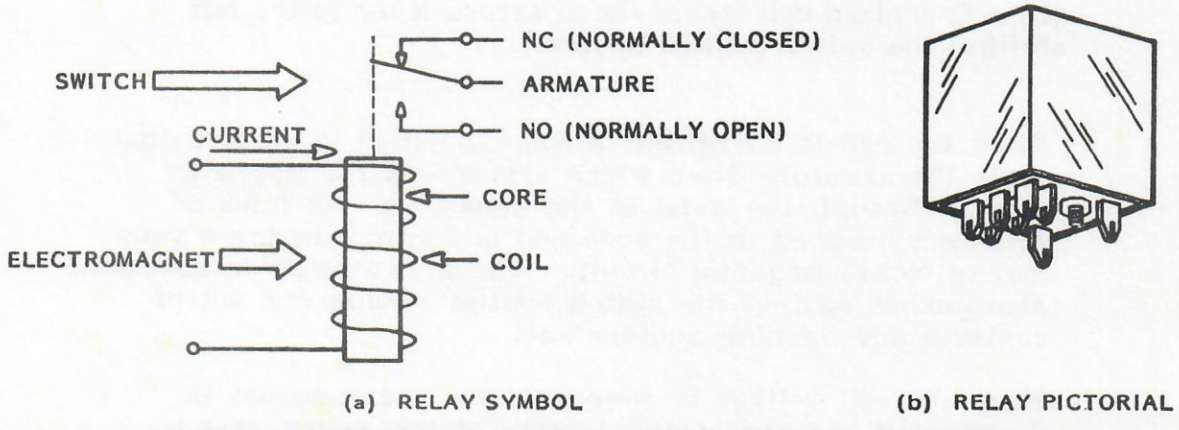


Figure 1 (a) - Relay circuit symbol and parts of a relay.
(b) - Relay pictorial.

When a voltage is applied to the coil a current flows creating a magnetic field. The magnetic field attracts the metal armature down to the core. As it does so, it breaks the connection between the armature and the normally closed (NC) contact and makes connection to the normally open (NO) contact. When the voltage is removed from the coil the armature is released and returns to the NC contact due to the spring action of the contact assembly.

The relay can be used to control a high current circuit with the low current coil. Note that there is no electrical connection between the coil and switch circuits.

RELAY CONSTRUCTION

A typical relay is built as shown in Figure 2.

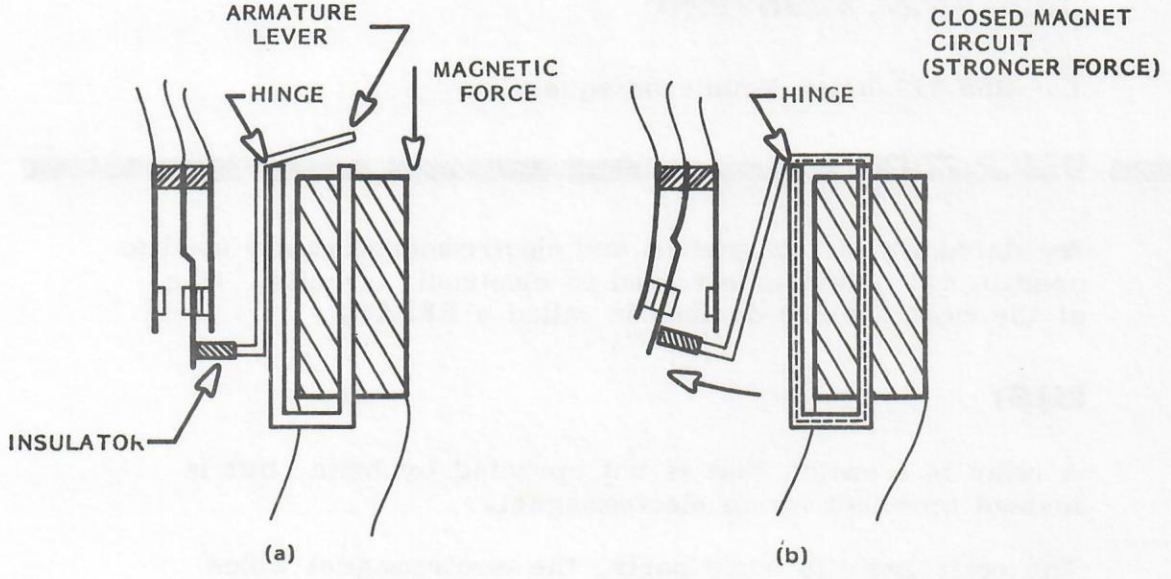


Figure 2 - Cross section view of a typical relay coil and armature. (a) - Deenergized with armature in rest position. (b) - Energized coil forces the armature lever to the left shifting the switch contact system.

When the coil is energized, a magnetic field is created that pulls the armature down which also closes the magnetic circuit through the metal in the armature. All lines of force are trapped in the core and armature creating a very strong closed magnetic circuit. The armature lever movement also pushes against the switch system closing one set of contacts and opening another set.

When the coil voltage is removed, the electromagnet is deactivated and the spring tension of the switch system pushes the armature lever back to the rest position.

COIL DATA

The relay coil is rated for a nominal voltage, typically 12 volts (CES 318) while others are rated at 6 volts, 24 volts or 115 volts. While 12 volts is the normal operating voltage for this relay, it will pull in at some lesser voltage (typically 7 volts) called the MINIMUM PULL-IN VOLTAGE.

Once the relay is activated, the magnetic circuit is closed and highly efficient. The voltage applied to the coil can be reduced and the relay will still stay energized. This coil voltage can now be lowered to approximately 1 or 2 volts before the armature releases. This is called the DROP-OUT VOLTAGE.

RELAY CONTACT ASSEMBLIES

The electrical switching circuits activated by the relay coil and armature lever can be very simple or complex. Typical switch assemblies are shown in Figure 3.

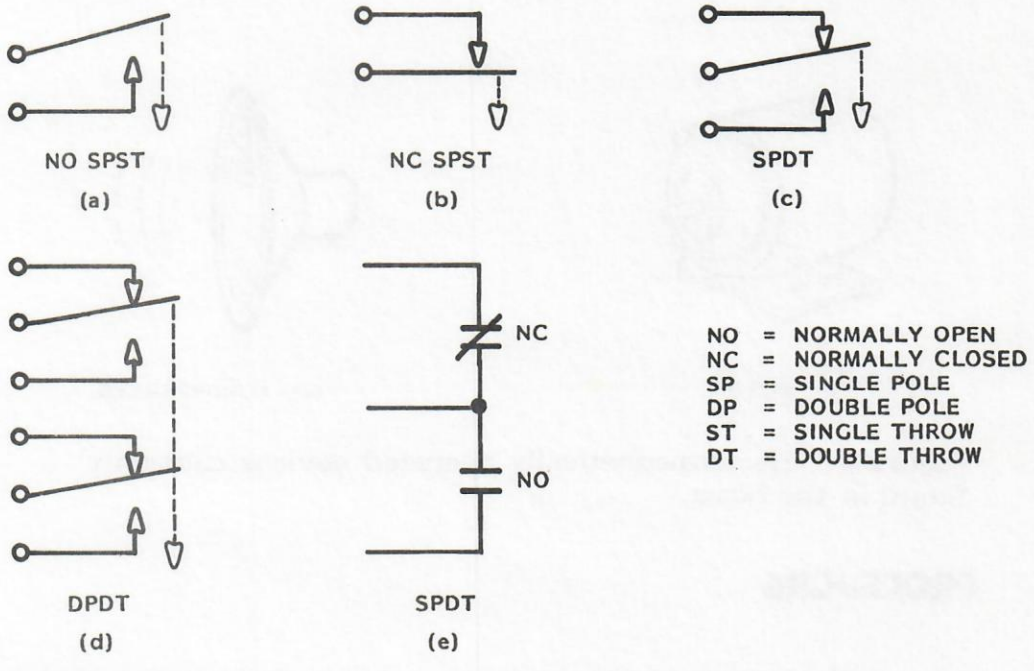


Figure 3 - Typical relay switch assemblies and symbols.

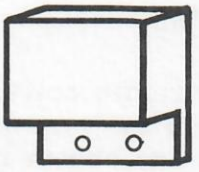
Another way of representing relay contacts used in electrical circuits is shown in Figure 3(e). The parallel lines with a diagonal line through them represent a closed contact (NC). Two parallel lines with no diagonal line through them represents an open contact (NO).

OTHER ELECTROMAGNETIC DEVICES

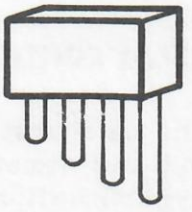
In addition to the relay described above, other electromagnetic devices that are frequently encountered in the home are doorbells and chimes and small motors as illustrated in Figure 4. Many types of microphones (dynamic) and most loudspeakers operate on magnetic principles. Electrical power generation is almost exclusively done using magnetic principles.

In this experiment you will examine the operation of a relay and make voltage tests and measurements. You will also connect the relay into a circuit that controls lights and another circuit that converts it to a buzzer.

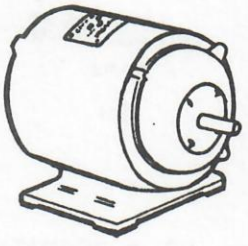
(a) DOOR BELL



(b) BUZZER



(c) DOOR CHIMES



(d) MOTOR

(e) LOUDSPEAKER

Figure 4 - Electromagnetically operated devices commonly found in the home.

PROCEDURE

3.1 . RELAY OPERATION

1. Plug the CES 318 relay card into the Printed Circuit (PC) socket on the Ed-Lab 651 panel as shown in Figure 5.

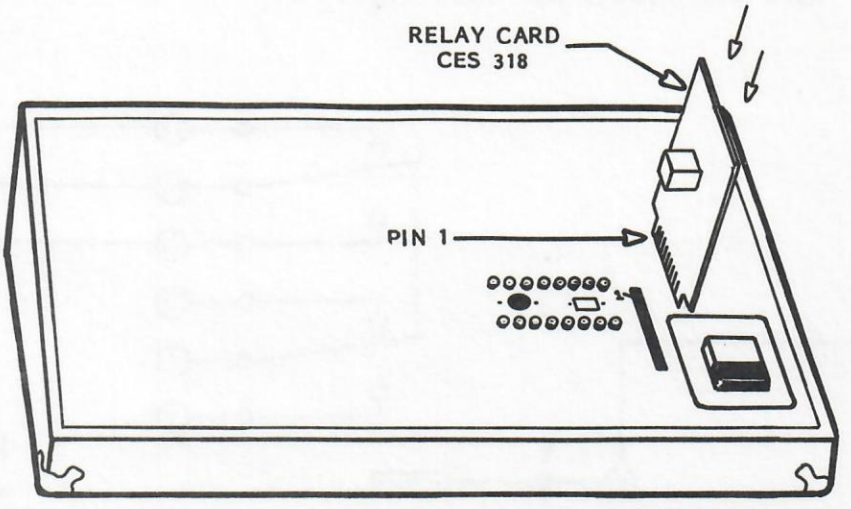


Figure 5 - Location of the PC socket on the Ed-Lab 318 Relay Module; EXPERIMENT.

Observe that pin 1 on the card must be aligned with the pin 1 marking on the panel. Connection may be made to the plug-in cards through the banana jacks labeled 1 to 16/14 as shown in Figure 5 above.

2. The circuit of the relay module and the numbers of the banana jacks needed to make connection to the relay are shown in Figure 6.

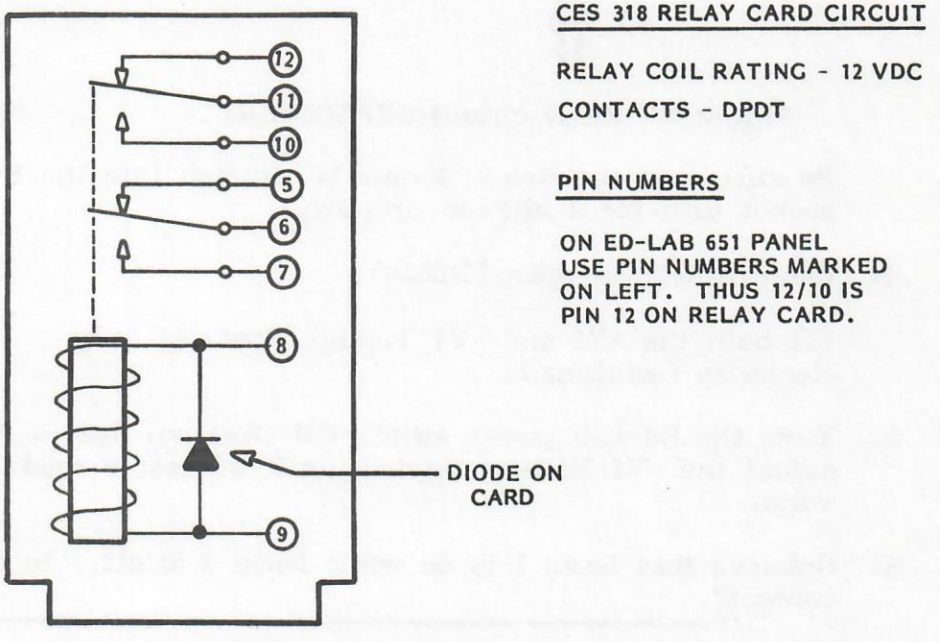


Figure 6 - Diagram and pin numbers of the CES 318 Relay Module that has a DPDT switching circuit. The diode is not involved in this experiment and its use is covered later.

3. Wire the circuit shown in Figure 7.

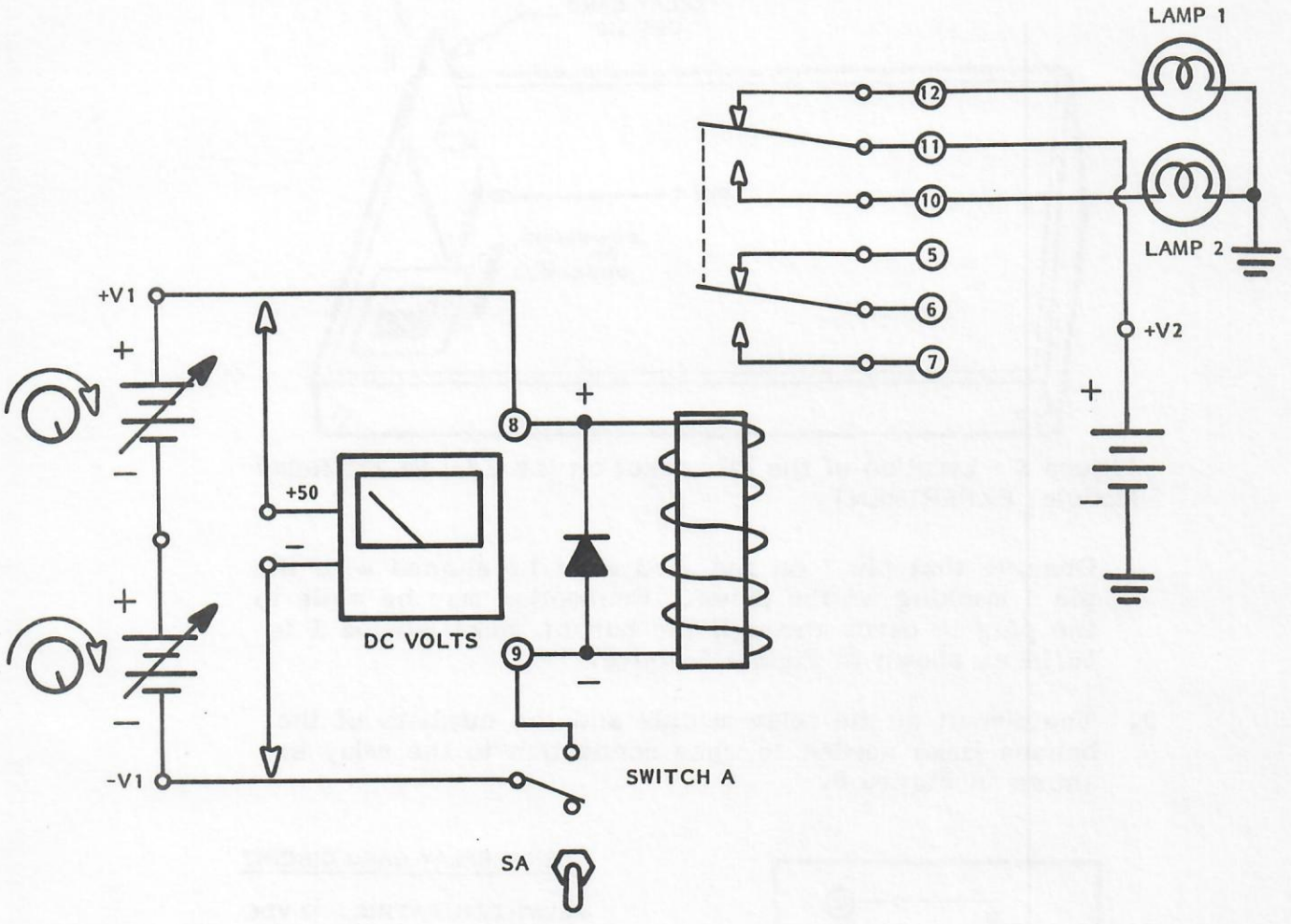


Figure 7 - Relay circuit EXPERIMENT.

Be sure that the Relay Module is plugged into the PC socket with pin 1 aligned properly.

4. Keep Switch SA open (DOWN).

   Set both the +V1 and -V1 Voltage Controls fully clockwise (maximum).

5. Turn the Ed-Lab power switch ON (but not Switch A) and adjust the -V1 Voltage Control until the meter reads 12 volts.

6. Observe that Lamp 1 is on while Lamp 2 is off. Is this correct? _____

7. Turn Switch SA ON (UP) and observe the lamp action and the movement of the relay contacts under the clear plastic cover.

   Describe the action of the relay. _____

   _____

   Describe the action of Lamps 1 and 2. _____

   _____

   _____

3.2 PULL-IN VOLTAGE

8. To determine the value of the PULL-IN VOLTAGE you must start with zero volts applied to the relay coil and raise the voltage until the relay operates. The minimum operating voltage is the PULL-IN VOLTAGE.

   Reduce the +V1 and -V1 Voltage Controls to zero (both knobs counter clockwise).

9. Gradually increase the +V1 Voltage Control until the relay operates as indicated by the contact movement, the clicking sound and the changing of Lamps 1 and 2. Be sure that the relay "clicks" in. The lamp may turn on before the relay is fully latched and held in position.

   Record the Pull-In voltage below.

   PULL-IN VOLTAGE = _____ V

10. Increase the relay coil voltage to the rated 12 volts.

3.3 DROP-OUT VOLTAGE

11. Once the magnetic circuit of the relay is closed, the lines of force are all trapped and the efficiency of the magnetic circuit is very high. While it took between 6 to 9 volts to PULL the relay in, it will take much less to HOLD it in.

12. Starting from the full +12 volts, reduce +V1 voltage gradually until Lamp 2 turns off and Lamp 1 turns back on.

Read this DROP-OUT voltage indicated on the meter and record the value below. You can lower the voltmeter range to +5V for a more accurate reading.

DROP-OUT VOLTAGE = _____ V

3.4 BUZZER OPERATION

One set of relay contacts can be used to turn the relay OFF after it has been turned ON. Once off, the armature returns to its rest position only to turn itself on again. This process repeats continually causing the relay to vibrate or buzz. This is the principal of the door buzzer.

13. Modify the relay circuit by changing the connection and adding one wire as listed below, and as shown in Figure 8.

    a. Disconnect the wire between Switch SA and pin 9 at the pin 9 end and connect it to pin 5 instead.

    b. Connect a wire between pins 6 and 9.

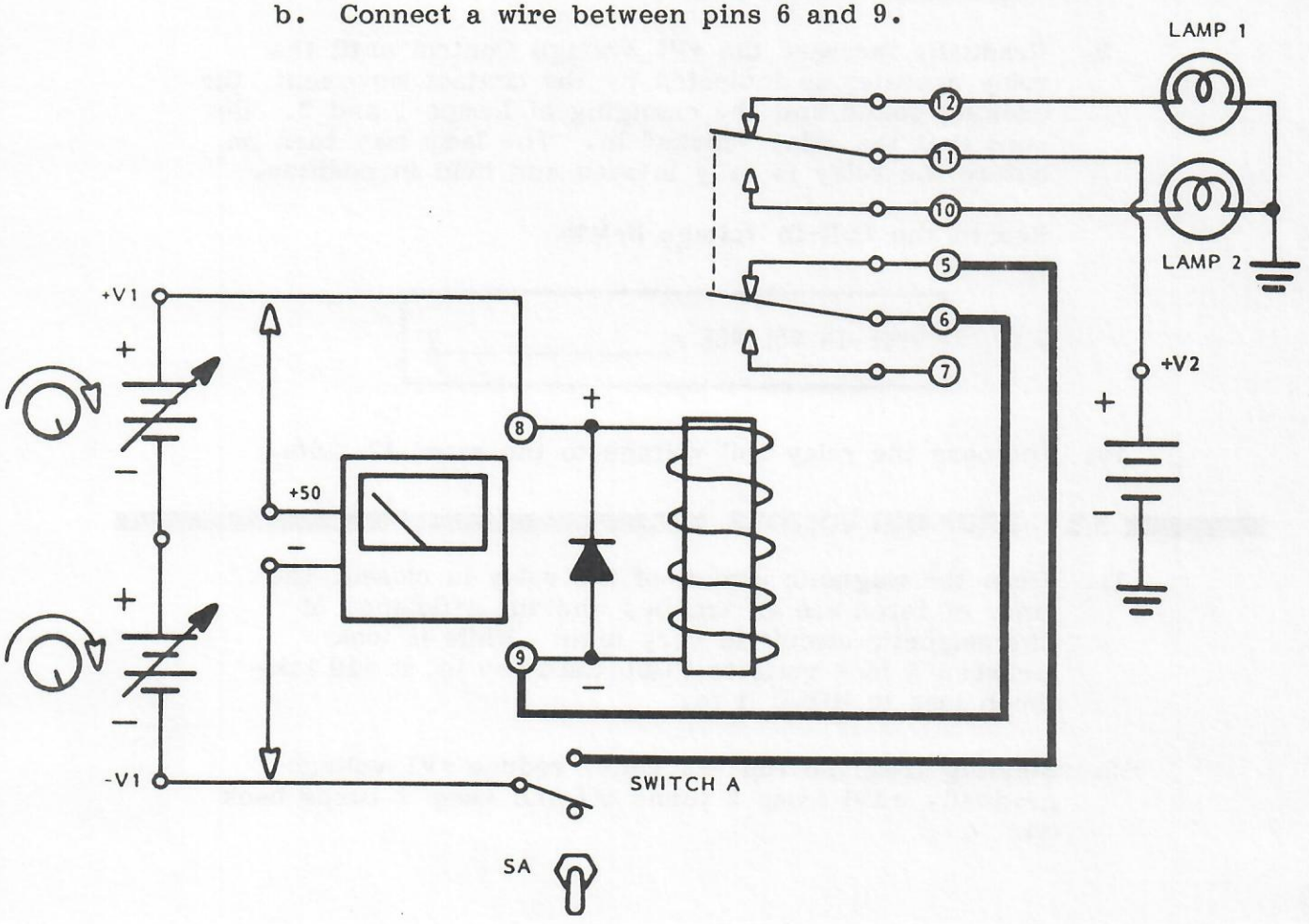


Figure 8 - Relay circuit modified for buzzer operation by adding the wires drawn with bold lines; EXPERIMENT.

14. Reset the voltage to 12 volts and listen to the sound made by the relay.

What causes the sound? _____

_____

Lower the voltage gradually until the buzzing stops and record the value.

BUZZ STOPS = _____ V

How did voltage affect the pitch of the sound? _____

_____

CONCLUSIONS

We have learned from this experiment that:

A relay is an electromagnetically operated switch.

The small relay coil current can be used to control large currents handled by the relay contacts.

There is no electrical circuit or connection between the relay contacts and the relay coil thus isolating the two circuits.

A relay coil has a rated nominal or operating voltage.

The relay will pull in at a lower voltage called the Minimum Pull-in voltage.

The relay, once pulled in, will hold in until the voltage is reduced to the Minimum Drop-out voltage.

The DPDT relay contacts on the CES 318 module can be used to control two separate circuits.

The CES 318 relay can be wired to act as a buzzer.

ASSIGNMENT

Answer the following True-False questions.

1. A relay is an electromagnetically operated switch. ____

2. A relay coil that is designed to operate at 115 V requires the full voltage to be applied before it will pull in. ____

3. Once a relay is energized it requires the full nominal voltage applied to the coil to hold it in. ____

4. The relay PULL-IN VOLTAGE is always greater than the DROP-OUT VOLTAGE. ____

5. A relay, when activated, produces an efficient magnetic circuit with a very strong holding force on the armature. ____

6. Placing a set of relay contacts in series with relay coil so that they open when the relay is energized, creates a buzzer. ____

DRAWINGS

7. Draw two SPDT relay switch contact assemblies using both the electrical and electronic symbols.

8. Draw a relay and contact assembly that has a 3PST Normally Open switching circuit.

9. Draw the circuit of a relay coil with a SPDT contact assembly wired to act as a buzzer.

10. List two other electrical or electronic devices that operate on electromagnetic principles.

KEY TERMS

1. ARMATURE

   The moving parts in an electromagnetic device. It is the movable part of a relay, buzzer or motor.

2. BUZZER

   A device used to generate an audible signal. The armature of the buzzer vibrates to produce a loud sound.

3. DROP-OUT VOLTAGE

   The voltage that can no longer hold the relay armature closed.

4. DPDT

   Double pole double throw switch or relay contact assembly.

5. DPST

   Double pole single throw switch or relay contacts.

6. NC

   Normally closed, referring to switch contacts.

7. NO

   Normally open, referring to switch contacts.

8. NOMINAL COIL VOLTAGE

   The stated value of voltage intended for normal relay operation. The relay, however, works over a range of voltages above and below the nominal value.

9. PULL-IN VOLTAGE

   The lowest voltage that will cause a relay armature to activate or "pull-in."

10. RELAY

    An electromagnetically operated switch.

11. SPDT

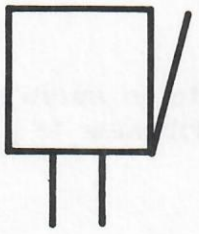
    Single pole double throw contact assembly.

12. DPDT

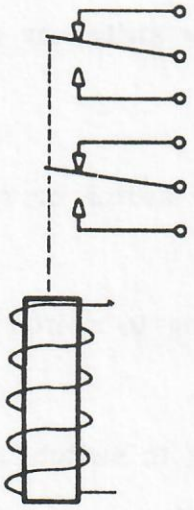
    Double pole double throw contact assembly.

CIRCUIT SYMBOLS

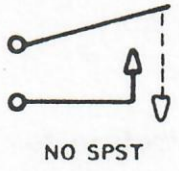
1. BUZZER



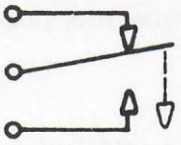
2. RELAY



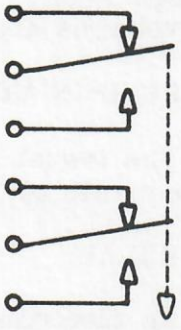
3. SWITCH AND RELAY CONTACTS



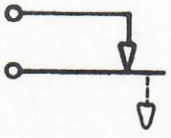
NO SPST



SPDT



DPDT



NC SPST

Latching Relay 4

OBJECTIVES

When you finish this experiment, you will be able to:

1. Draw the relay circuit symbols used for low current, low level electronic circuits using the NARM symbols.
2. Draw the relay circuit symbols used for high current industrial circuits using the NEMA symbols.
3. Draw an electrical control Ladder diagram.
4. Draw and explain the operation of the basic relay latching circuit.
5. Explain the operation of the remote On-off relay latching control circuit.
6. Show how additional Remote Control On-off stations can be added to the relay latching circuit.

ADDITIONAL EQUIPMENT

a. CES 318 Relay Module Card or equal

DESCRIPTION

In the previous experiment, Relays, the relay symbols introduced are used for low current and low level voltages (often called low level "signals"). These low level relay symbols are recommended by the National Association of Relay Manufacturers (NARM) and are shown in Figure 1.

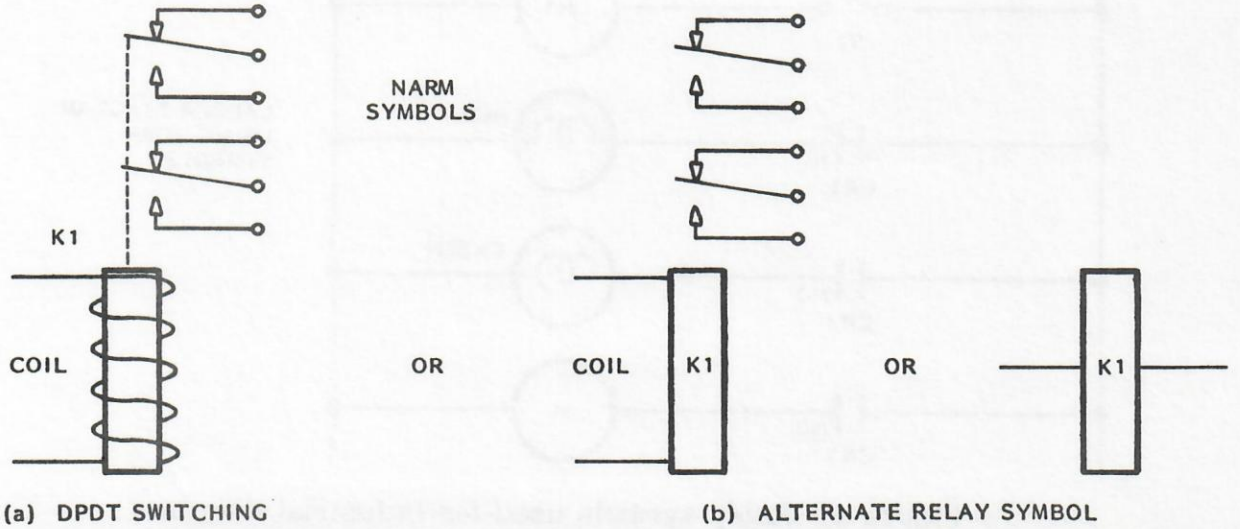


Figure 1 - Low current low level relay symbols adopted by the National Association of Relay Manufacturers (NARM).

Where industrial control circuits require the use of relays to control large motors and other high current devices, the symbols used for relays are different. The Joint Industrial Council (JIC) and the National Electrical Manufacturers Association (NEMA) have adopted the relay symbols which are shown in Figure 2.

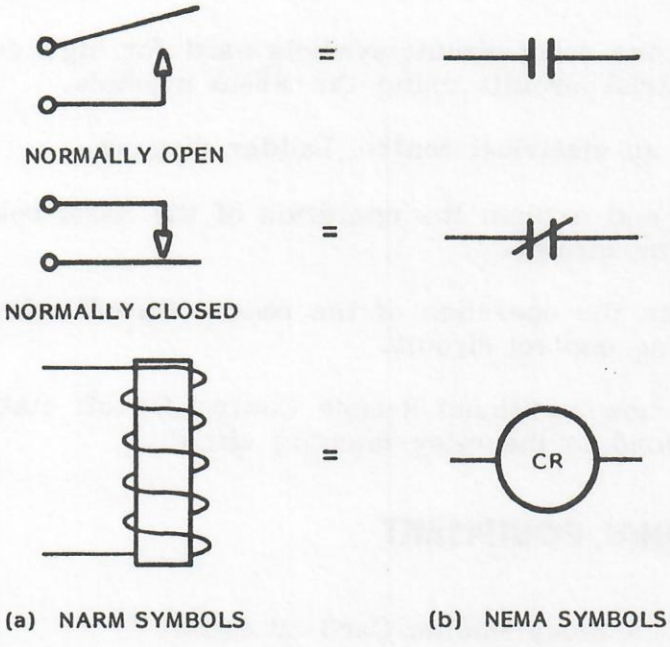


Figure 2 - Comparison of the relay symbols used by NARM (a) and NEMA (b).

A typical circuit using the National Electrical Manufacturers Association symbols is shown in Figure 3.

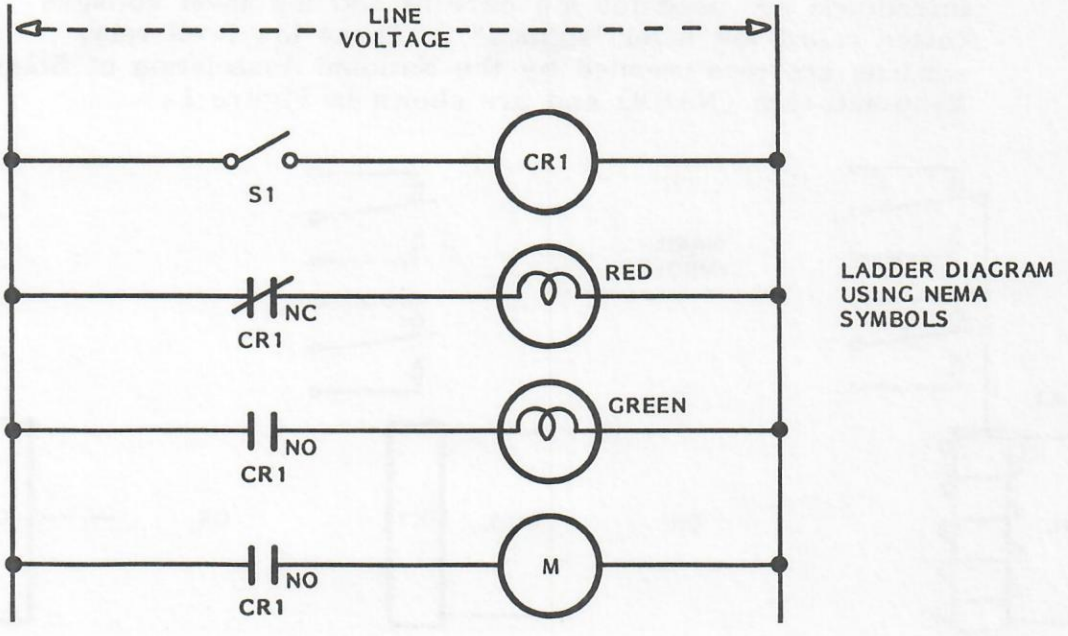


Figure 3 - Relay symbols used for industrial diagrams adopted by NEMA. The drawing format is called a Ladder Diagram.

In the circuit of Figure 3, the relay coil is the circle at the top labeled CR1 (Control Relay 1) and it is activated by manual switch S1. When relay coil CR1 is placed across the power line by closing switch S1, all contacts labelled CR1 are activated. The CR1 Normally Closed (NC) contacts (indicated by the diagonal bar) open and the red light turns off. The two sets of Normally Open (NO) contacts close turning on the motor (M) and the green light. In more complex circuits, relay CR1 often energizes a second relay coil which would be labeled CR2. All contacts controlled by this second relay would also be labeled CR2 in the diagram.

LADDER DIAGRAM

The type of circuit drawn in Figure 3 is known as a LADDER DIAGRAM because the two power line wires are drawn as the vertical members and each parallel section of the circuit is drawn horizontally resembling a ladder rung.

The use of the Ladder diagram format tends to simplify the circuit drawing as the relay contacts can be placed anywhere in the drawing thus shortening the lines.

Relay circuits of this type, used for control in manufacturing plants, are called MAGNETIC CONTROLLERS. Large, modern, industrial control systems use a digital computer instead of relays to control circuits and are known as PROGRAMMABLE CONTROLLERS.

RELAY LATCHING CIRCUIT

Relay LATCHING circuits, also called LOCK-UP circuits, have several applications one of which will be explored in this experiment. The basic latching circuit is shown in Figure 4(a). Switch S1 powers the relay coil and when the relay pulls in, contacts 1 and 2 "short-out" S1 since they are in

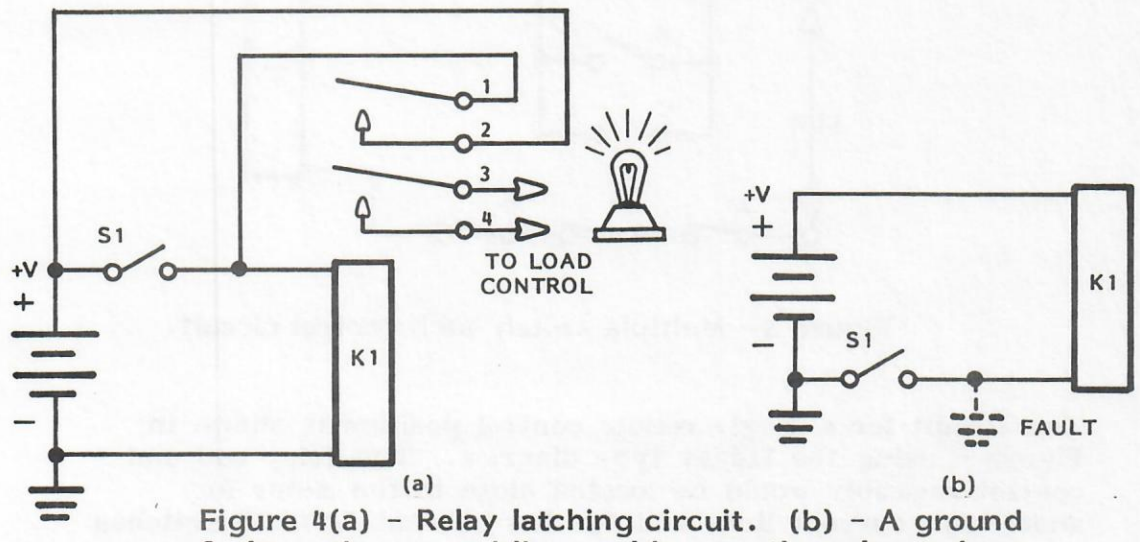


Figure 4(a) - Relay latching circuit. (b) - A ground fault on the ground line could cause the relay to be powered accidentally.

parallel with S1. Switch S1 is no longer needed to control the relay coil and can be released; the relay is LATCHED. To release the relay, the +V source must be removed from the relay coil to open contacts 1 and 2 as shown later.

As shown in Figure 4(a) the relay coil is normally controlled by switching the +V line. If the switch is placed in the ground line, Figure 3(b), an accidental ground will energize the relay creating the possible hazard of equipment being turned on unexpectedly. If, in the circuit of Figure 3(a), there is an accidental ground on the +V line, a fuse will be blown or a circuit breaker will turn off but the relay will not be energized. Thus the control switch is normally placed in the +V line.

MULTIPLE REMOTE ON-OFF CONTROL

A major application for the latching relay circuit is ON/OFF control of a high current circuit from one or more remote locations. A simple version is shown in Figure 5 below. Switches A, B and C are normally open and either one can turn on the relay to energize the load. Also shown are switches D, E and F which are normally closed. Either one can turn off the relay to deenergize the load. The shortcoming of the circuit in Figure 5 is that if switch A' (or B' or C') is in the OFF position (open), switches A, B or C cannot turn the relay on nor can switches B' or C' affect the operation. Momentary switches are usually used.

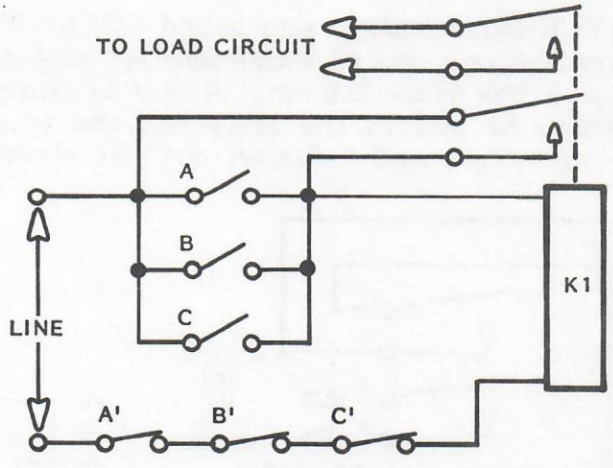


Figure 5 - Multiple switch latch control circuit.

The circuit for a single remote control position is shown in Figure 6 using the ladder type diagram. The relay coil and contact assembly would be located close to the motor for short high current lines and the low current ON/OFF switches can be remotely located.

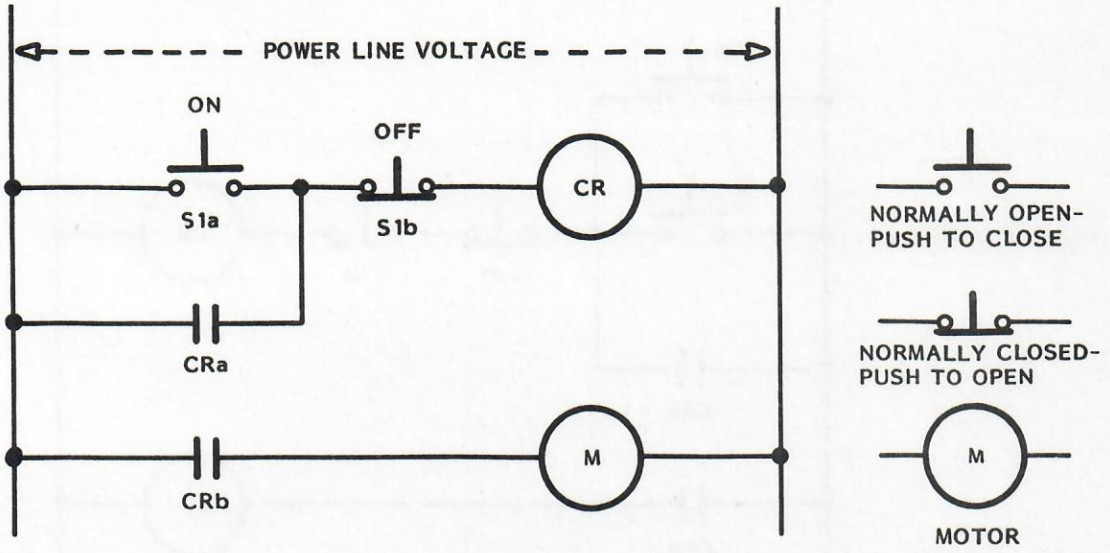


Figure 6 - ON/OFF relay latching control circuit.

Switches S1a and S1b shown in Figure 6 are the symbols used to represent MOMENTARY CONTACT switches also referred to as BUTTONS. Switch S1a is normally open (NO). When pressed, the switch closes contact but opens again immediately upon release. Switch S1b is a normally closed (NC) momentary contact and opens when depressed. When released, the switch immediately returns to its closed state.

ON-OFF CIRCUIT OPERATION (Figure 6)

When, in Figure 6, switch S1a is depressed momentarily, relay coil CR is energized. One set of contacts, CRb, energizes the load, a motor. The second set of contacts, CRa, shorts out switch S1a. Thus, when S1a is released which would normally open the circuit, the relay coil is still energized through the path provided by contacts CRa. To shut the motor off it is necessary to depress the normally closed switch, S1b, to break the relay coil circuit which opens contacts CRa, unshorting S1a.

To add remote On-Off control stations, the ON switches are paralled and the OFF switches are placed in series as shown in Figure 7. Any number of control stations can be added in this manner.

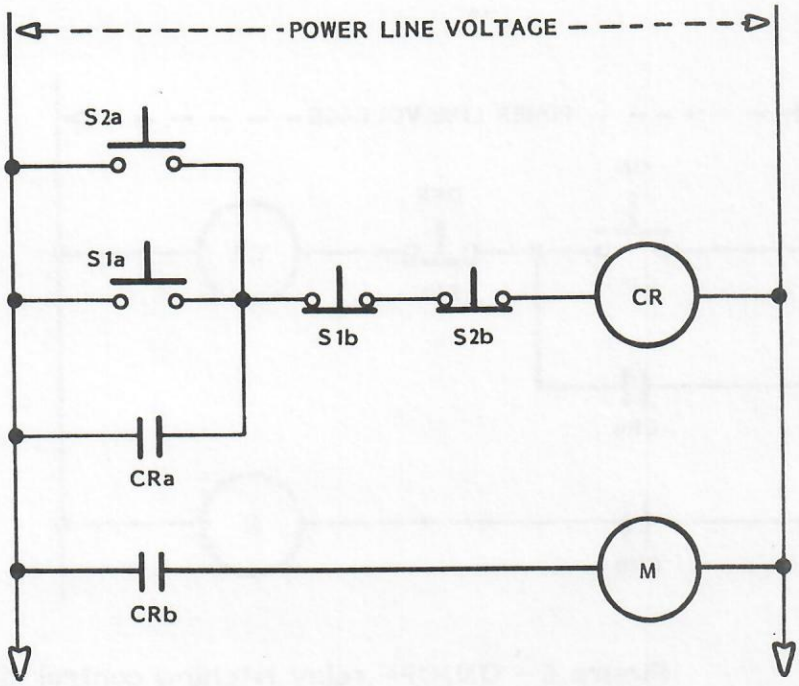


Figure 7 - Two remote control circuits (S1a, b and S2a, b) can control motor M.

In this experiment you will wire a two position remote control system using the four switches mounted on the panel.

PROCEDURE

1. The on-off remote control circuit diagram will be wired using the CES 318 Relay Card. The NARM symbol for this relay is shown in Figure 8(a) and is then redrawn in (b) using NEMA format. To simplify the drawings, the NEMA symbol is used in this experiment.

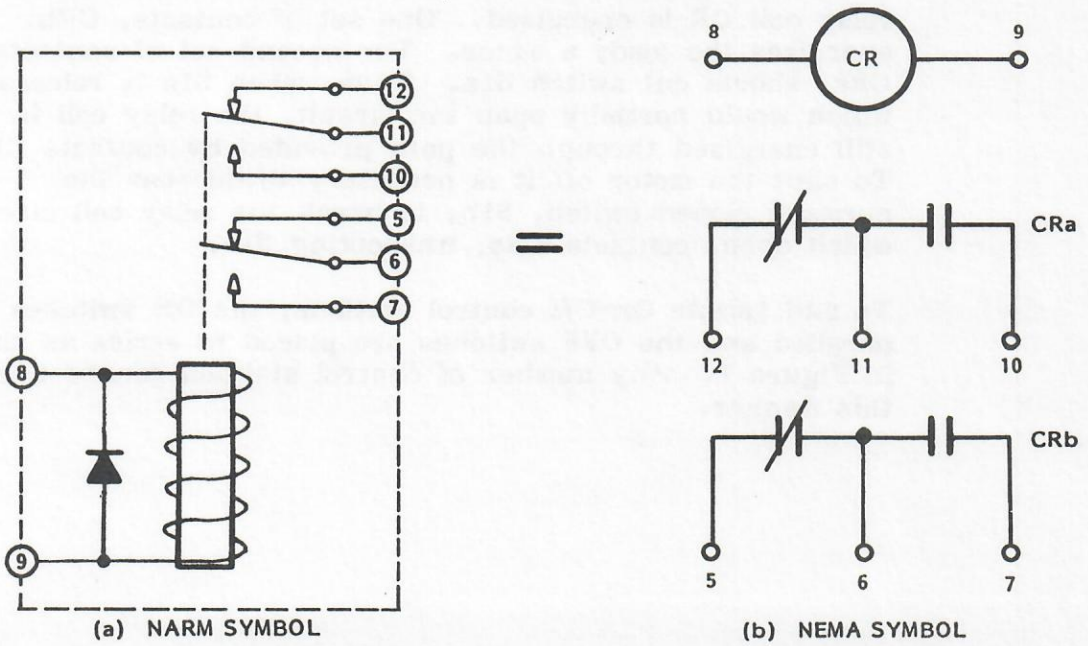


Figure 8 - The CES 318 Relay card symbol in (a) NARM and (b) NEMA format.

2. Plug in the CES 318 Relay Module to the PC connector with the relay facing left and 1 on the relay card at the upper left hand side of the connector.

3. Wire the circuit shown in Figure 9. Note that this diagram is for a relay controlled lamp, the same as the previous experiments but uses the ladder diagram schematic.

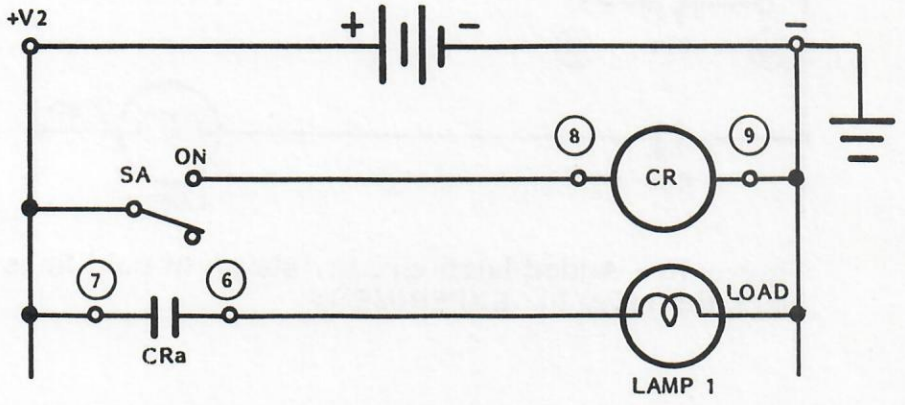


Figure 9 - Basic relay control circuit EXPERIMENT.

4. Because the trainer has toggle switches only and no momentary switches, we will consider that DOWN is the normal switch position. To activate the switch we place it in the UP positon momentarily, then DOWN again.

4.1 RELAY CONTROL OPERATION

5. Move Switch SA to the UP positon to energize the relay which, in turn, will energize the load, Lamp 1.

   Does Lamp 1 light when Switch SA is placed in the UP position?

6. Turn the circuit ON and OFF several times, leaving Switch SA in the DOWN position.

   Does the lamp turn ON and OFF following the switch action?

4.2 LATCH OPERATION

7. Add the two wires, shown by the lines marked A in Figure 10, to result in the Latching Circuit. Connect pins 10 and 11 directly to the Switch SA jacks.

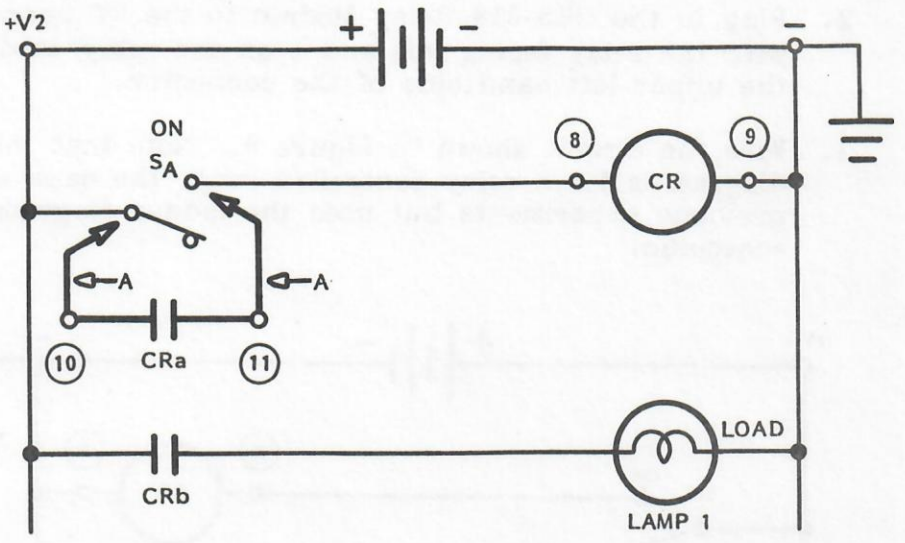


Figure 10 - Added latch circuit, shown in bold lines, locks the relay in; EXPERIMENT.

8. Place Switch SA in the Up positon. The relay should energize and light Lamp 1.

   Does Lamp 1 light? _____

9. Place Switch SA in the DOWN position. What happens to Lamp 1? _____

   _____

4.3 RELEASE CIRCUIT

10. It has been shown above that Switch SA, acting as a momentary contact switch, can energize the circuit but cannot turn the circuit off. It is necessary to add an OFF switch to the circuit. The first step is outlined below.

    Remove the wire (dotted line in Figure 11) that connects Switch SA and contacts CRa at pin 8 of the relay.

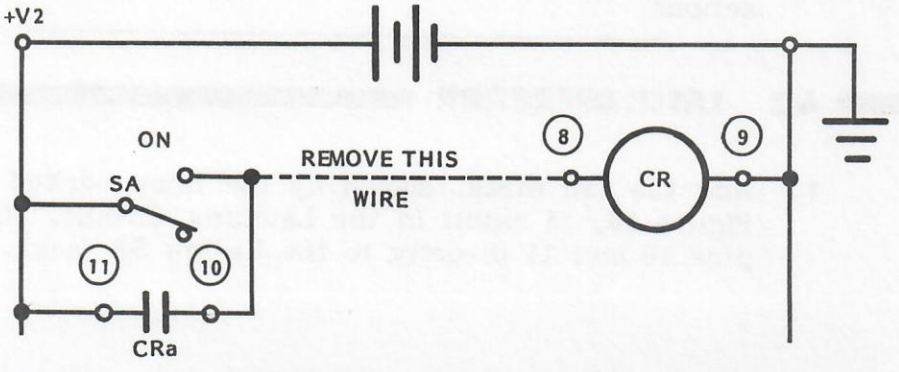


Figure 11 - Remove the wire shown by the dotted line; EXPERIMENT.

11. Add Switch SB, the OFF switch, to the circuit as shown by the wires marked with the letter B in Figure 12.

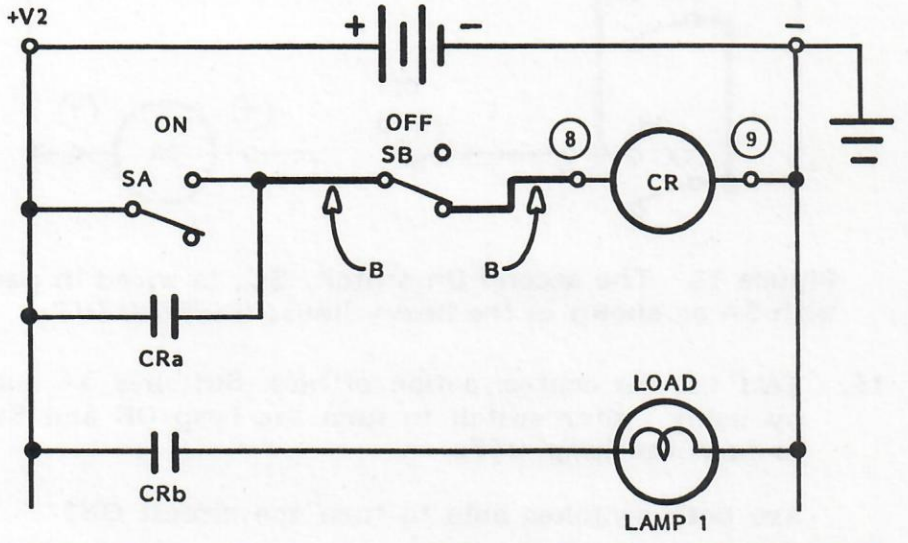


Figure 12 - Addition of the Off switch, SB; EXPERIMENT.

12. Place both SA and SB in the Down position.

    Turn the Ed-Lab power OFF, then ON again.

    Turn the circuit ON by moving SA, the ON switch, UP and then DOWN immediately (simulating a button switch).

    Does the load, Lamp 1, turn on and stay on? _____

13. Turn the circuit OFF using SB, the OFF switch, by moving Switch SB UP and then DOWN immediately.

    Does Lamp 1 turn off and stay off? _____

    Considering Switches SA and SB as momentary contact switches, you have, in effect, wired the ladder circuit shown earlier in Figure 6 which is the same as the circuit in Figure 12.

4.4 DUAL ON SWITCHES

14. Add a second On switch as shown in Figure 13 by placing Switch SC in parallel with switch SA.

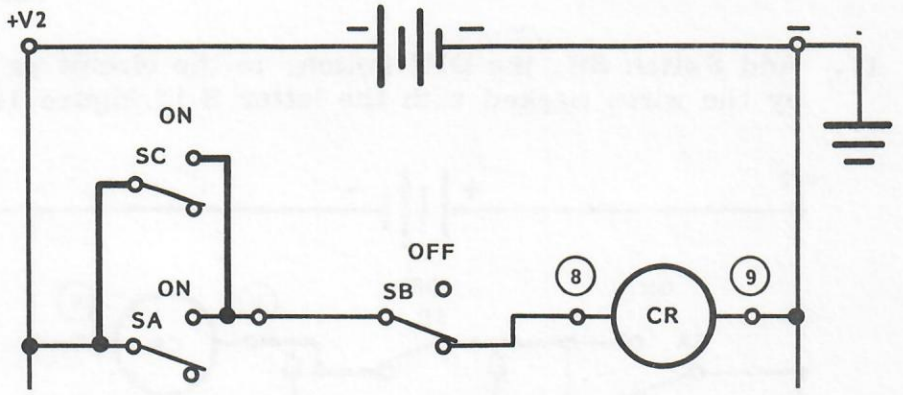


Figure 13 - The second On switch, SC, is wired in parallel with SA as shown in the heavy lines; EXPERIMENT.

15. Test the On control action of both Switches SA and SC by using either switch to turn the lamp ON and Switch B to turn the lamp OFF.

    Are both switches able to turn the circuit ON? _____

4.5 DUAL ON-OFF SWITCHES

16. The OFF controls must be placed in series as explained earlier. Add Switch SD to the control circuit as shown by the added heavy lines in Figure 14 by first removing, at both ends, the wire going to jack 8 and then adding the two wires to Switch SD, marked C.

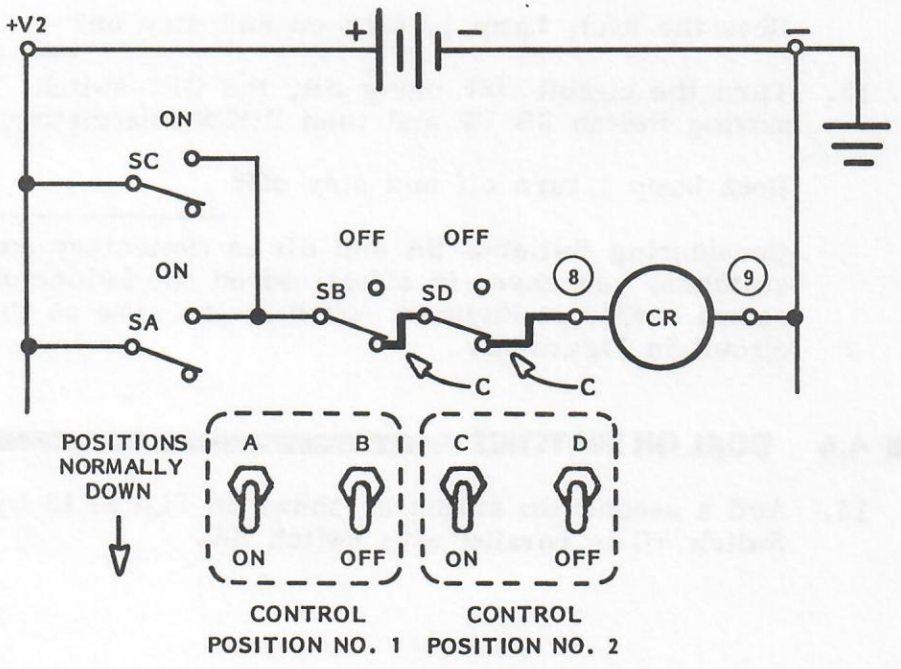


Figure 14 - Complete two position ON-OFF remote control system with Switch SD wired in series with SB as shown by the heavy lines; EXPERIMENT.

17. Place all four switches in the DOWN position.

Turn the system ON from positon No. 1 using Switch SA and then turn it OFF using SB.

Turn the system ON from positon No. 2 using Switch SC and turn it OFF using SD.

Turn the system ON from positon No. 1 using Switch SA and OFF from position No. 2 using SD.

Observe how the system can be turned ON and OFF from either of the two control positions, SA-SB or SC-SD.

4.6 LADDER DIAGRAM

The ladder diagram for the complete system you have wired is shown below.

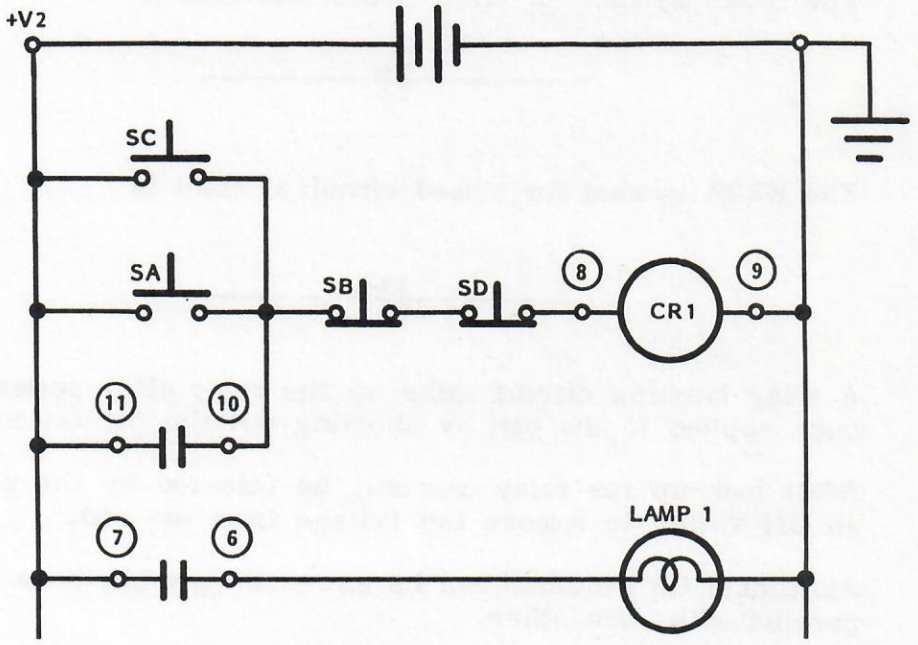


Figure 15 - Ladder Diagram.

CONCLUSIONS

We have learned from this experiment that:

There are two symbols used to indicate a relay. The National Association of Relay Manufacturers (NARM) uses electronic symbols for low signal level relays. The National Electrical Manufacturers Association (NEMA) uses a different symbol for industrial power applications.

The NEMA symbols are used in Ladder diagrams which can be clearer and simpler than the diagrams drawn using the NARM symbol.

The NEMA symbol for the coil is

The NEMA symbol for open circuit contacts is

The NEMA symbol for closed circuit contact is

A relay latching circuit locks up the relay after power has been applied to the coil by shorting out the On switch.

After lock-up the relay can only be released by the use of an Off switch to remove the voltage from the coil.

Additional On switches can be added by placing them in parallel with each other.

Additional Off switches can be added by placing them in series with each other.

The On switches are momentary contact NO types.

The Off switches are momentary contact NC types.

ASSIGNMENT

Answer the following multiple choice questions.

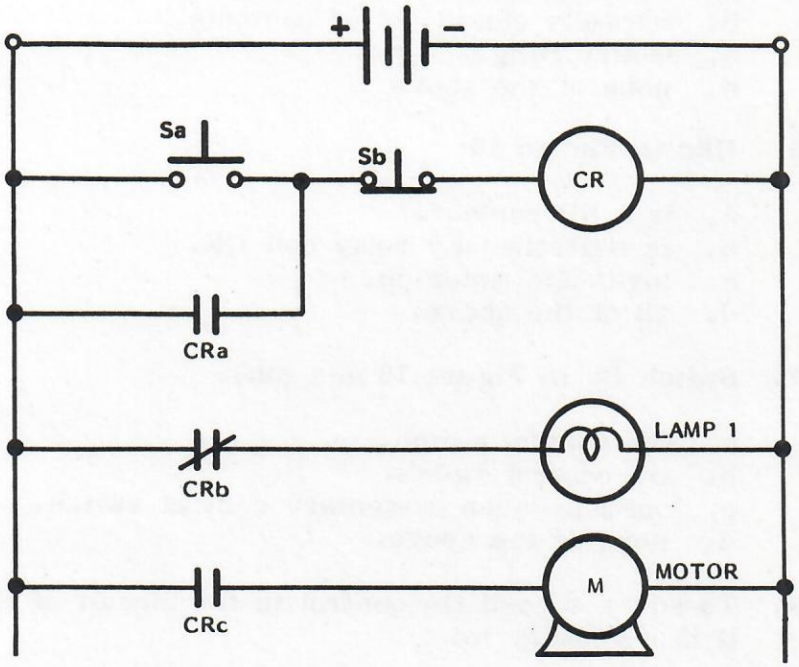


Figure 16 refers to questions 1 to 10.

1. The drawing format of Figure 16 is referred to as a:

   a. pictorial diagram.
   b. ladder diagram.
   c. rectangular diagram.
   d. rung diagram.

2. Switch Sa in Figure 16 is:

   a. a normally closed toggle switch.
   b. a normally closed momentary contact device.
   c. used to turn the motor on.
   d. used to turn Lamp 1 on.

3. CRa in Figure 16 is a:

   a. normally open pair of contacts controlled by CR.
   b. normally closed pair of contacts controlled by CR.
   c. manually operated momentary contact switch.
   d. set of contacts that energizes the motor, M.

4. When Sa, in Figure 16, is depressed:

   a. CR is energized.
   b. lamp 1 turns off.
   c. the motor is energized.
   d. all of the above.

5. CRb in Figure 16 is a:

   a. normally open set of contacts.
   b. normally closed set of contacts.
   c. ladder rung.
   d. none of the above.

6. CRc in Figure 16:

   a. is a NO contact.
   b. is controlled by relay coil CR.
   c. turns the motor on.
   d. all of the above.

7. Switch Sb in Figure 16 is a (an):

   a. Off control switch.
   b. On control switch.
   c. normally open momentary contact switch.
   d. none of the above.

8. To add a second On control to the circuit of Figure 16 it is necessary to:

   a. place a switch in series with Sa.
   b. wire a switch in parallel with Sb.
   c. change CRa from NO to NC contacts.
   d. none of the above.

9. To add a second Off switch to the circuit of Figure 16, it is necessary to add a switch similar to:

   a. Sb in series with Sb.
   b. Sa in series with Sa.
   c. Sa in parallel with Sb.
   d. none of the above.

10. When the relay coil in Figure 16 is energized, relay contacts:

   a. CRa short out Switch Sa causing latching.
   b. CRb turns Lamp 1 on.
   c. CRc drops open to shut off motor.
   d. all of the above.

KEY TERMS

1. JIC

   Joint Industrial Council

2. LADDER DIAGRAM

   A form of drawing where the power source lines are drawn vertically and components that are wired across the power line are drawn horizontally as rungs in a ladder.

3. LATCHING CIRCUIT

   A circuit where the relay contacts are used to lock the relay in the energized position by shorting out the relay energizing switch.

4. LOW LEVEL RELAY

   A relay used to control low current and voltage levels often referred to as low level signals. The symbol used for low level relays are shown in Figure 1(a).

5. NARM

   National Association of Relay Manufacturers.

6. NEMA

   National Electrical Manufacturers Association.

Burglar Alarm 5

OBJECTIVES

When you finish this experiment, you will be able to:

1. Explain the operation of a magnetic sensor switch.
2. Learn problem solving methods using relays and switches.
3. Draw the circuit of an alarm system that has a latch, Set switch and Arm/Disarm switch.
4. Explain the operation of the alarm system.
5. Wire and test the burglar alarm system.

ADDITIONAL EQUIPMENT

a. CES 318 Relay Module or equal

DESCRIPTION

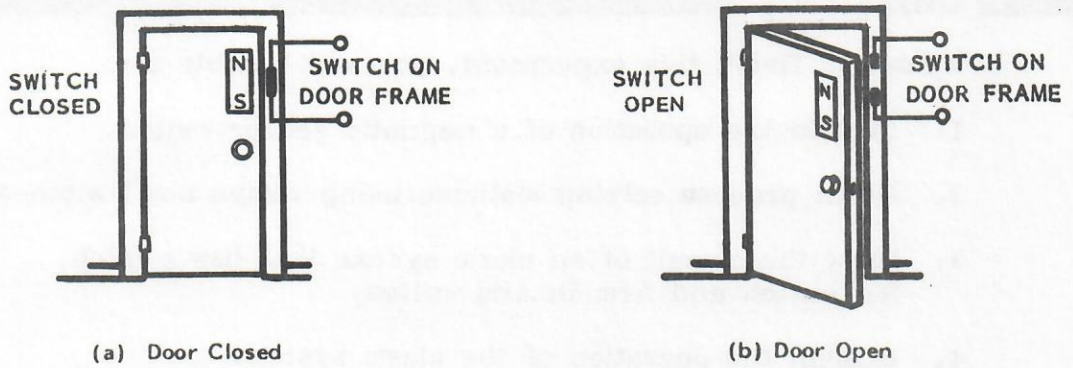
Another application for the latching relay circuit from the previous experiment is the Burglar Alarm. The alarm is used to protect the perimeter of a house by sensing when windows and doors are opened and sounding an alarm even though the windows or doors may be closed again.

PROBLEM SOLVING

This experiment is a good illustration of how relays and switches are used to solve real circuit problems. We will develop a basic burglar alarm circuit, step-by-step, solving each problem as it arises.

SENSORS

Each door and window in a house is usually protected by a switch that is magnetically operated and is of the type shown in Figure 1.



(a) Door Closed (b) Door Open

Figure 1 - Switch contacts are closed when magnet is close (a) and open (b) when magnet is removed.

The switch is secured to the door or window frame. The magnet is mounted to the door or window in such a position that the switch is a closed circuit when doors and windows are shut. An open door or window results in an open switch.

Each window is usually protected by a circuit which consists of a foil around the window glass plus the magnetic switch. When the window is opened the magnetic switch breaks the circuit and if the glass is broken the foil breaks, opening the circuit.

BASIC ALARM CIRCUIT

A basic simplified alarm circuit is shown in Figure 2 where we see that all the magnetic sensor switches and the window foils must be wired in series with a voltage source and the relay coil.

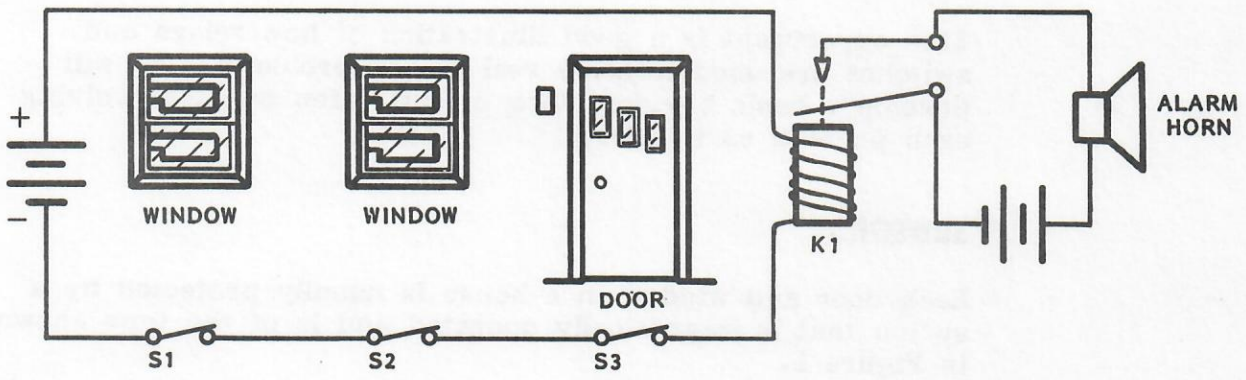


Figure 2 - Basic Alarm System

When all the windows and doors are closed, switches S1 to S3 are closed and relay K1 is energized. The relay armature is pulled down and the alarm horn is silent because the horn circuit is open. Should any of the windows or the door open, relay K1 would deenergize turning the alarm ON. But, if the person entering were quick enough, the window or door could be shut after entry and there would only be a brief sound of the alarm horn because it would stop when the relay coil circuit was completed again. This is a major problem in a practical alarm system using this simple circuit.

Reviewing this problem, we decided that a latching circuit is needed so that the alarm will continue to sound after the door or window is closed again.

ALARM LATCHING CIRCUIT (PINS 3 AND 4)

A latching circuit similar to the type described earlier in Experiment No. 4 can now be added so that once the relay is deenergized, it will be "locked-out." The latching effect will cause the alarm to continue to sound even if the open door or window is closed again.

Using latching contacts on the relay is not quite so simple because it is necessary to have a method to START or ACTIVATE the circuit and a way to UNLATCH or DEACTIVATE it. A latched alarm system is shown in Figure 3 using two control switches.

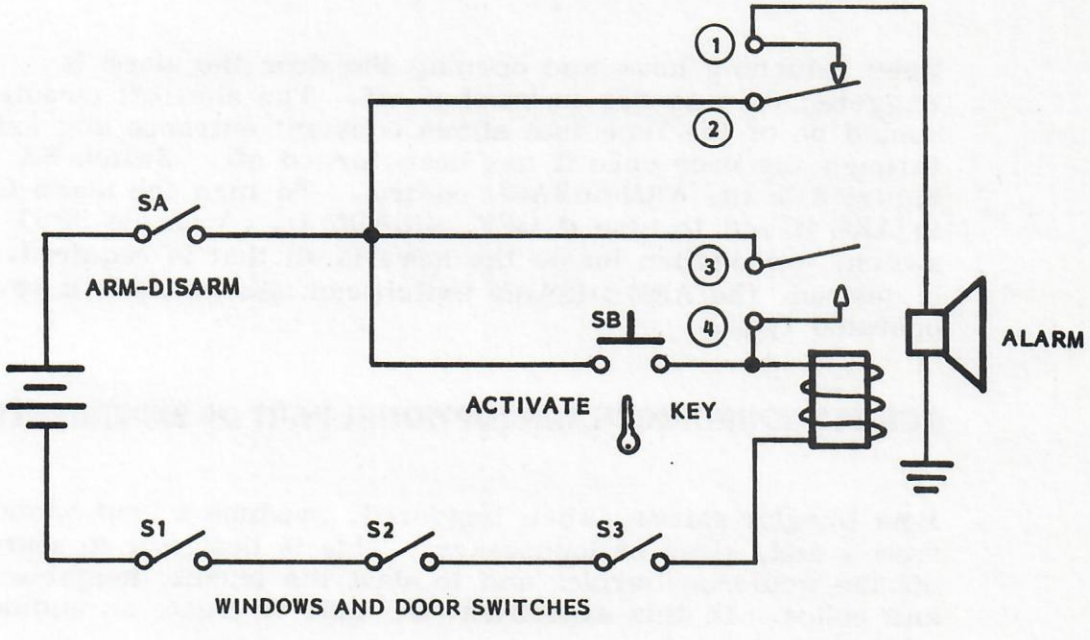


Figure 3 - Burglar Alarm with latching circuit.

The Normally Open contacts 3 and 4 on K1 are wired in series with the relay coil. Thus, when any break occurs in the coil circuit such as an open S1, S2 or S3, the coil deenergizes and the 3-4 contacts open. Now, even if the offending switch is closed again, the relay cannot be reenergized as the 3-4 contacts are open. The alarm horn will sound continually.

The remaining problem is to SET the alarm energizing K1 in the first place and to shut it off when returning home.

ACTIVATE CONTROL SWITCH (SB)

Now that the alarm will stay ON with the latch, the next problem to be solved is a way to ACTIVATE the alarm when leaving the house and a way to turn it OFF when returning. A control or ACTIVATE switch must be added to activate the circuit or turn on the relay after leaving the house. A Normally Open key operated switch is placed on the outside door frame and wired into the circuit. This is Switch SB in Figure 3, marked ACTIVATE.

The ACTIVATE switch, SB, in parallel with the 3-4 contacts of the relay, can now close the circuit to allow the relay to pull in. Once the relay is energized Switch SB is no longer needed to keep K1 energized and can be opened.

ARM-DISARM SWITCH (SB)

When returning home and opening the door the alarm is triggered ON and has to be shut off. The shut-off circuit should be of the type that allows constant entrance and exit through the door once it has been turned off. Switch SA in Figure 3 is the ARM-DISARM control. To turn the alarm ON is to ARM it and to turn it OFF, DISARM it. A simple SPST switch, well hidden inside the home is all that is required. If desired, the ARM-DISARM switch can also be made a key operated type.

AUDIBLE SOUNDING ALARM (OPTIONAL PART OF EXPERIMENT)

Most burglar alarms, when triggered, produce a loud sound from a bell, siren or loudseaker. This is designed to scare off the would-be burglar and to alert the tenant, neighbors and police. In this experiment we want to create an audible alarm.

The audible alarm requires the use of three additional components and devices, two of them new, that will be studied in detail later but used here. The device to be used again is the transistor which will amplify or strengthen the alarm tone.

The first new device to be used is the FUNCTION GENERATOR located in the center area of the Ed-Lab trainer panel. It will be used as a source of the alternating voltage to provide a tone. The Function generator is the subject of a later information sheet and experiment.

The second new device to be used is the LOUDSPEAKER, also on the Ed-Lab trainer panel. The function of a speaker is to convert electrical impulses to equivalent sound.

LOUDSPEAKER OPERATION

The construction of a basic loudspeaker is illustrated in Figure 4 below.

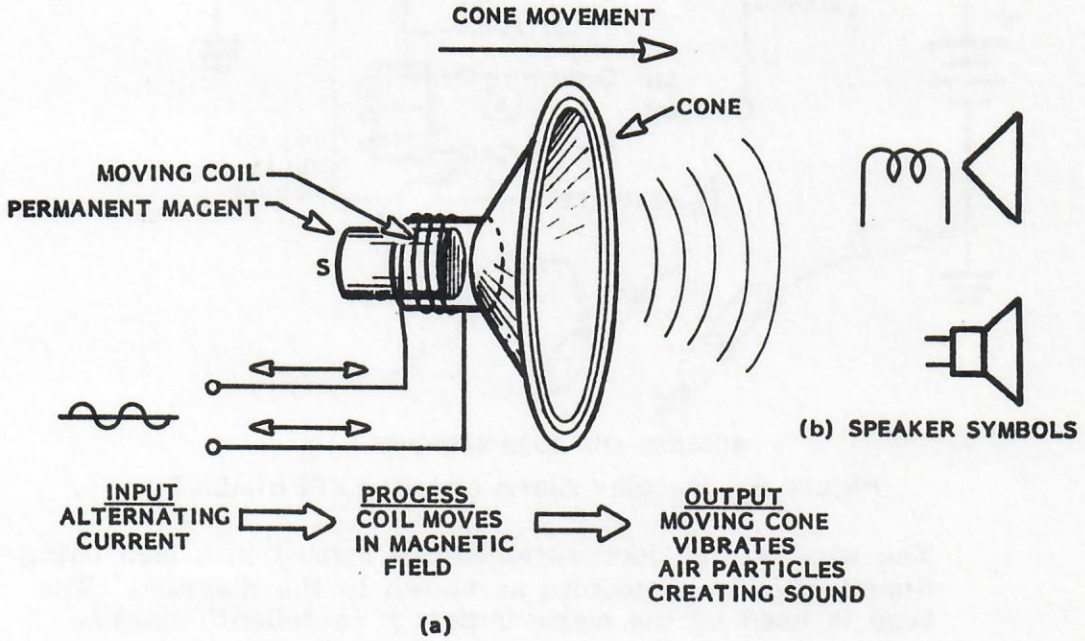


Figure 4(a) - Speaker changes electrical signal to an audible signal. (b) - Speaker symbols.

An ac signal is applied to the moving coil (also called a VOICE COIL) of the speaker as shown in Figure 4. The current flowing through the coil creates a magnetic field that interacts with the fixed magnetic field and causes the cone to move back and forth. The cone moves air particles that creates sound.

An ac signal source (the Function Generator) and the loudspeaker will be used to provide an audible alarm signal in the optional part of this experiment.

PROCEDURE

1. Wire the burglar alarm circuit shown in Figure 5.

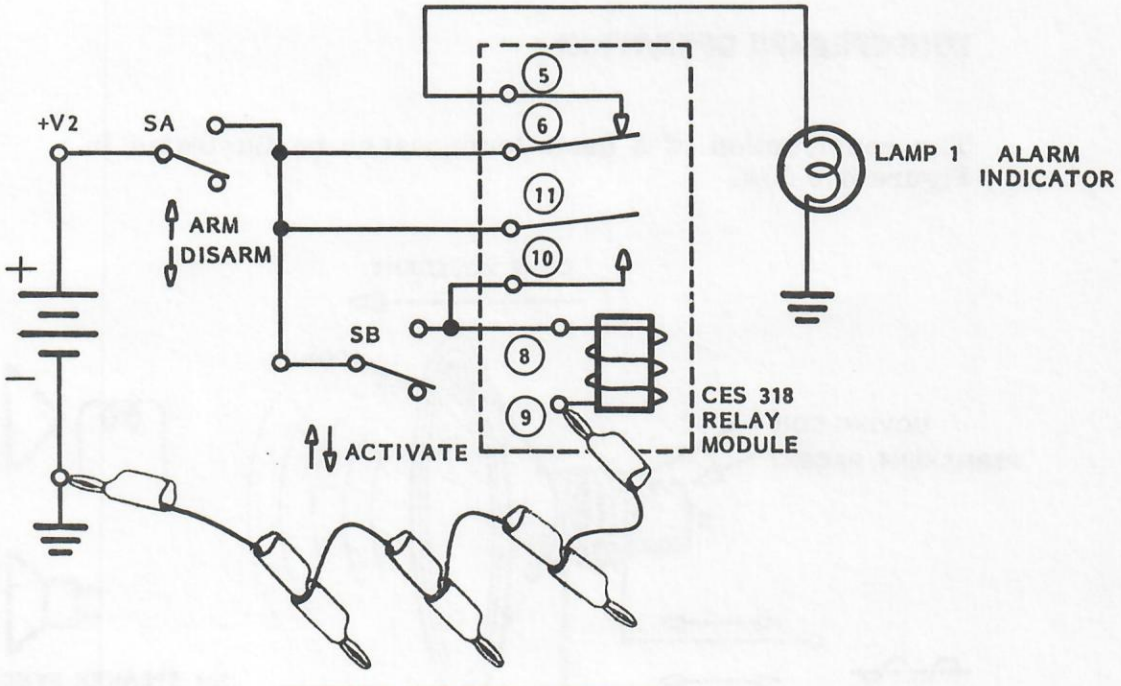


Figure 5 - Burglar Alarm circuit EXPERIMENT.

The window and door switches are formed in a loop using Stacking Jack connectors as shown in the diagram. The lamp is used as the alarm indicator (a "silent" alarm).

5.1 TESTING THE ALARM

2. Plug in the CES 318 Relay Module with the relay on the left and the pin 1 of the card aligned with the pin 1 marking on the panel.

3. Set Switches A and B DOWN in the normal Alarm OFF positions.

   Does Lamp 1 light? _____

   Should Lamp 1 light? _____

4. You are now leaving the house. Arm the alarm circuit by setting Switch A to the UP position and leave it there.

   Does Lamp 1 light? _____

   Why? _____

   _____

   _____

5. Activate the circuit by moving Switch SB UP and then DOWN again (momentary contact) to SET the alarm system.

   Has Lamp 1 turned OFF? _____

6. The alarm is now activated and any break in the perimeter circuit will trigger the alarm.

   Break the perimeter circuit at any of the external plugs simulating the window and door switches and reconnect the plug.

   Does the alarm trigger and turn Lamp 1 on? _____

   Does Lamp 1 turn off when the plug is reconnected? _____

   Will disconnecting any of the other plugs produce the same effect when opened? _____

   _____

   *Keep all wiring for the next part of the experiment.

5.2 AUDIBLE ALARM (OPTIONAL)

The Audible Alarm circuit addition is shown in Figure 6 and consists of the Function Generator, Transistor Q7 and the Loudspeaker.

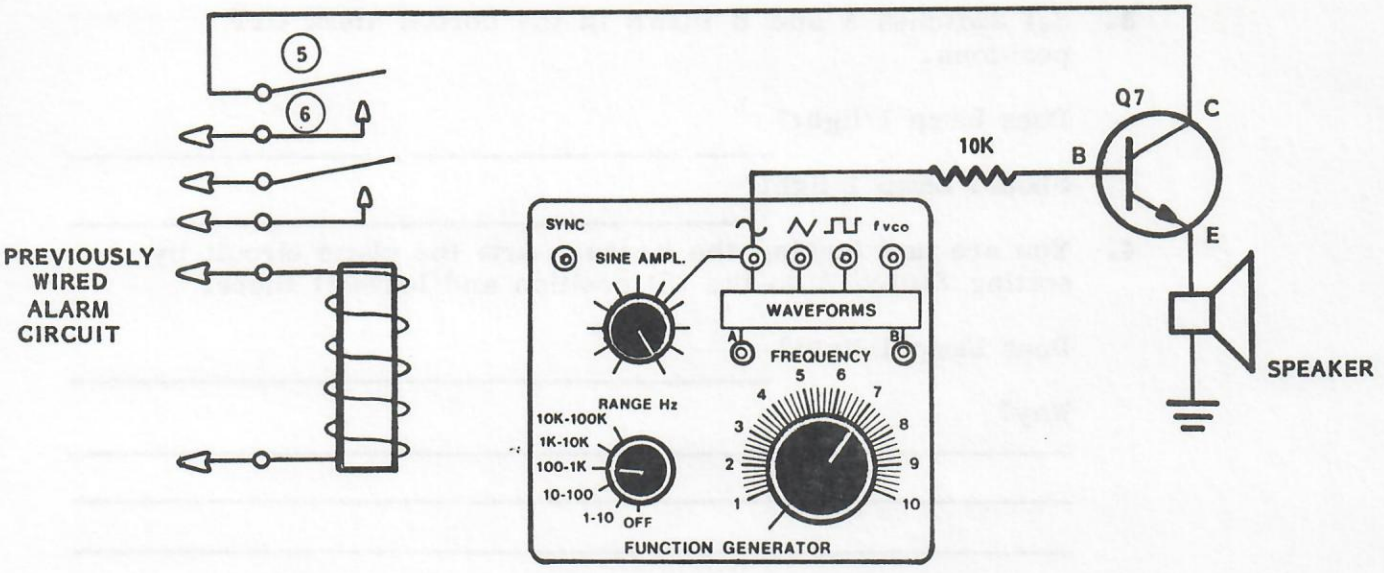


Figure 6 - Addition of the Audible Alarm; EXPERIMENT.

7. Add the Audible Alarm circuit shown in Figure 6, as follows:

   a. Remove the wire from Lamp 1 (that connects to 5 on the relay card and connect it to the collector (C) of transistor Q7.

   b. Wire the sinewave output of the Function Generator to the base (B) of Q7 through a 10K series resistor.

   c. Wire the speaker from the emitter (E) of Q7 to ground.

8. Set the Function Generator controls as shown in Figure 6 to produce a 700 Hz ac voltage.

   Set Switch SA DOWN to the DISARM position and set Switch SB DOWN also.

9. ARM the alarm by placing SA UP.

   Do you hear a tone from the speaker? _____

   ACTIVATE the alarm by moving Switch SB UP and then DOWN again.

   Does the tone stop? _____

10. Trigger the alarm by breaking the perimeter circuit at one of the plugs and then DISARM the circuit by moving SA DOWN.

    Does the tone come on and then turn off? _____

5.3 ADDITIONAL IMPROVEMENTS

11. We would prefer to have a system with a single switch inside the house that would allow us a 30 second delay to leave the house before the alarm is activated. This is left as an unsolved problem at this time.

CONCLUSIONS

We have learned from this experiment that:

Another application for the latching relay circuit is for a simple burglar alarm.

In a basic burglar alarm each door is monitored by a magnetic switch and each window by a magnetic switch and foil on the glass.

A magnetic switch is closed circuited when placed next to its associated magnet. If a window or door is opened the magnet moves away from the switch and the switch circuit opens.

All the sensor switches are wired in series with a voltage source and relay coil.

The relay powers a visual or audible alarm.

The relay is wired so that once triggered it latches and cannot be released.

Two switches are needed to operate the basic alarm system, the ARM/DISARM and ACTIVATE switches.

ASSIGNMENT

Answer the following True-False questions.

1. A magnetic sensor switch is closed circuited when placed next to a magnet. ____

2. The sensor switches for each door and window are wired in parallel or series, whichever is more convenient. ____

3. The burglar alarm relay circuit described in this experiment is latched by the removal of voltage from the coil. ____

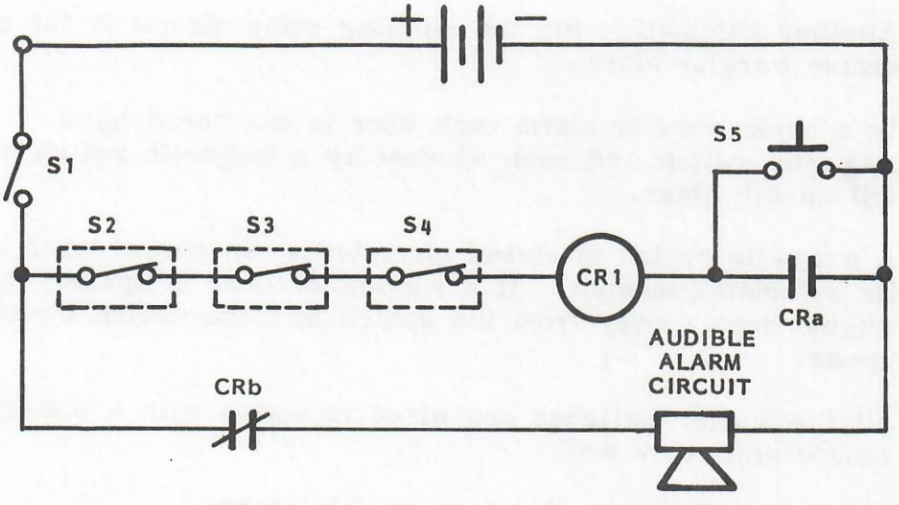


Figure 7 - Refers to questions 4 to 9.

4. The circuit shown in Figure 7 is identical to that shown earlier in Figure 5 but drawn in the ladder diagram form. ____

5. When the circuit of Figure 7 is to be armed, Switch S1 must be closed and Switch S5 depressed momentarily. ____

6. If the circuit of Figure 7 is to be expanded to protect more windows and doors, each magnetic sensor switch added must be placed in series with S2, S3 and S4. ____

7. The function of Switch S1 in Figure 7, is to set the alarm when it is turned on. ____

8. The function of Switch S5 in Figure 7 is to Arm or Disarm the alarm when entering or leaving the house. ____

9. In Figure 7, contacts CRa and CRb are magnetically operated switch types, CRa being NC and CRb, NO. _____

10. If a very tall window is to be protected against forced entry it is possible to use two magnetic sensors, one at the top and another at the bottom of the window but the two sensor switches must be wired in parallel. _____

KEY TERMS

1. ACTIVATE/DEACTIVATE SWITCH

   The switch used to apply or remove power to the alarm system.

2. ARM/DISARM SWITCH

   The switch used to set the alarm system to protect the premises against unwanted entry.

3. LOUDSPEAKER

   A device used to convert electrical energy to equivalent sound energy.

4. MAGNETIC SENSOR SWITCH

   A switch that is activated by a magnetic field.

INFO SHEET 3

Electromagnetic Induction Principles

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Identify what is meant by an expanding or collapsing magnetic field.
2. Describe the effect of a changing magnetic field upon the free electrons in a conductor.
3. Describe the effect of moving a conductor through a magnetic field.
4. Define what is meant by INDUCTION.
5. State and explain FARADAY'S LAW.
6. State and explain LENZ'S LAW.

DISCUSSION

Information Sheet 2 and Experiments 2 and 3 showed that electrons in motion through a conductor create a magnetic field. The reason given was that each moving electron has a magnetic field about it and, when all electrons are flowing in the same direction, the fields combine to produce a stronger field. The more electrons in the current flow, the stronger the field and so the strength of the magnetic field about a wire is controlled by the current flow. As the current increases it creates an "expanding" field and a decreasing current causes a "shrinking" or "collapsing" field.

INDUCTION

Current, which is a flow of free electrons, has lines of magnetic force around it. The inverse situation is also true. When lines of an external magnetic field "cut" across a wire, the free electrons in the wire will move, resulting in a current flow. This behavior is called INDUCTION because there is no direct connection between the wire and the source of the magnetic field. The current flow is said to be INDUCED.

The various conditions for inducing a voltage in a conductor are illustrated in Figure 1.

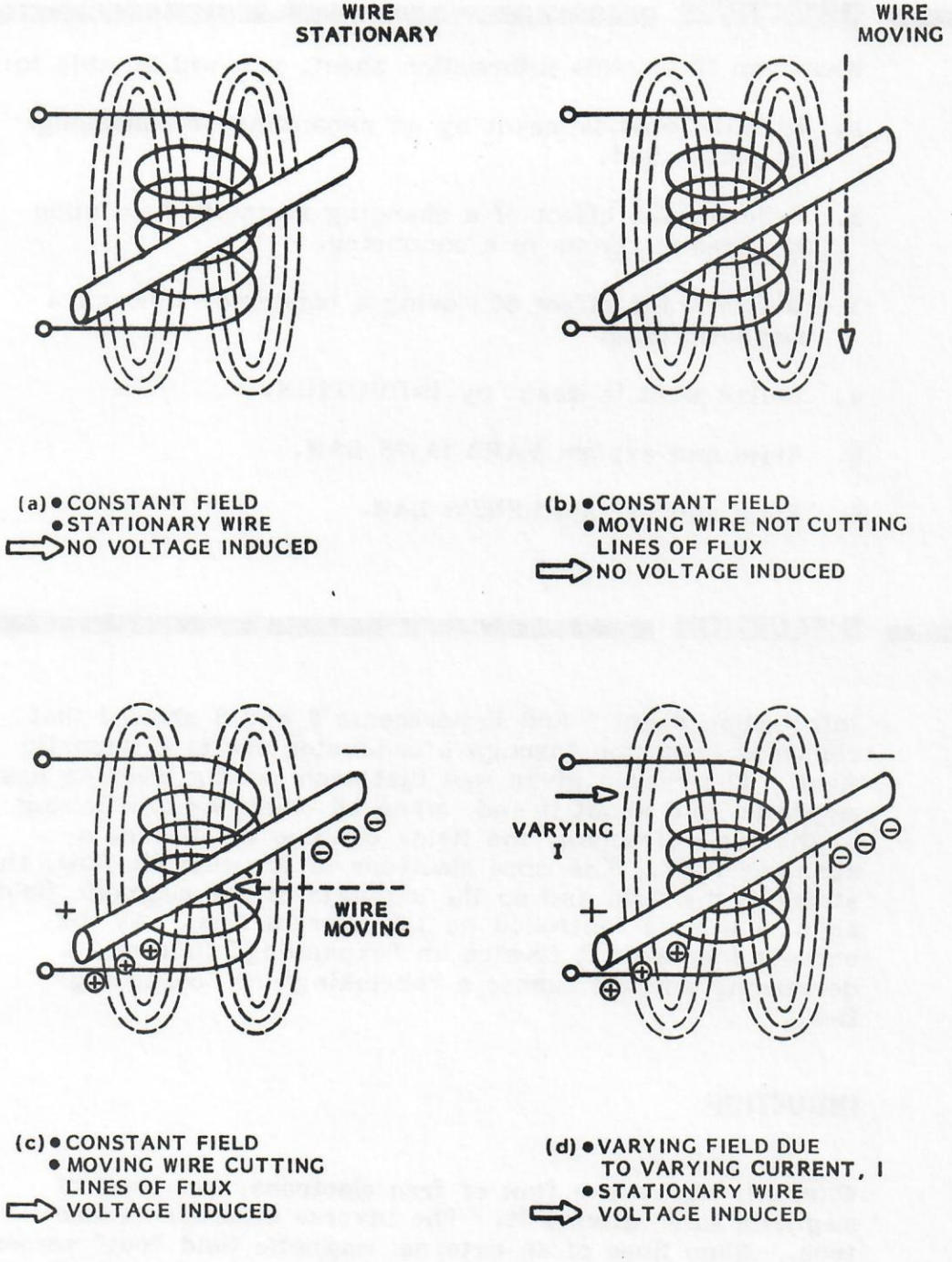


Figure 1 - Conditions under which voltage is induced in a conductor.

If the wire in which the voltage is induced is in a complete circuit, then a current will flow. If the wire is an open circuit as shown in Figure 1 then no current flows but a voltage is developed across the wire. This is the principal of the rotary magnetic electrical generator.

Another drawing explaining induction is shown in Figure 2 using a constant magnetic field developed by a permanent magnet.

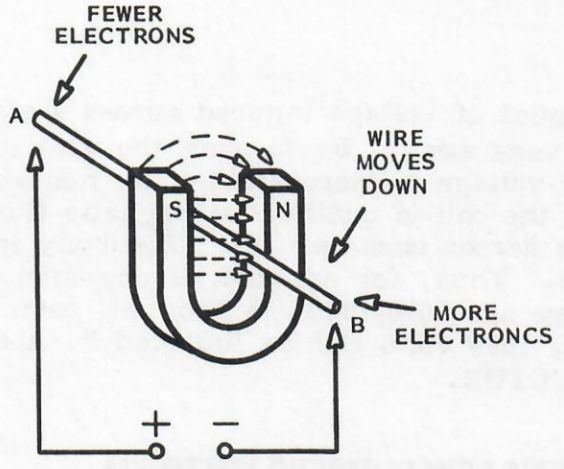


Figure 2 - Voltage induced across a wire as it moves through a magnetic field.

When the conductor is moved through the magnetic field, the free electrons in the conductor are forced to one end of the conductor by the magnetic field. This creates a difference of potential, a voltage, across that wire. To generate this induced voltage, the following conditions are needed.

1. There must be motion; either the wire must physically move through the field or the magnetic field flux must move across the wire by a physical motion of the field or a variation in field strength.

2. The wire and magnetic lines of force contributing to the induction must be perpendicular to each other (90°).

The polarity of the induced voltage is determined by two factors. These are:

1. The direction of movement of the wire relative to the field. Reversing the direction of movement will reverse the induced voltage polarity.

2. The direction of the magnetic field. Reversing the magnetic field polarity will reverse the induced voltage polarity.

If, in Figure 2, the wire is moved upward instead of downward, the polarity across the wire will reverse and end A will be negative and B positive.

COILS

The amount of voltage induced across a single length of wire will be very small. By forming the wire into a coil, the induced voltage is increased by the number of turns. Each turn of the coil is cut by the magnetic flux and the induced voltages across each turn are effectively in series additive. Thus, for example, if one turn generates 1 volt and there are 1000 turns in the coil, each time the field cuts the coil, 1000 volts will be "induced." A coil is also called an INDUCTOR.

FARADAY'S LAW (INDUCED VOLTAGE)

The English physicist Michael Faraday (1791 - 1867) discovered the principle of Electromagnetic Induction in 1831 and formulated the following law.

> FARADAY'S LAW - The size or magnitude of the emf or voltage generated in a conductor by a magnetic flux is directly proportional to the number of turns in the conductor and the amount of magnetic lines of flux and how fast the flux cuts the conductor (rate of change).

Faraday's law can be expressed as

$$v_{INDUCED} = N \frac{\Delta \Phi}{\Delta t}$$

Where v_{IND} = induced voltage across the coil in volts
N = number of turns in the coil
$\Delta \Phi$ = magnetic flux in Webers
Δt = speed, in seconds, at which the flux cuts the coil

The Greek letter delta (Δ) represents the "difference" or change. The symbol for voltage is no longer a V or E but a lower case v or e. This indicates that the voltage is not a steady state value but varies, and therefore v is an "instantaneous" value that varies with time.

Faraday's law is illustrated in Figure 3 where a bar magnet is shown being inserted into a coil (a) and withdrawn from the coil (b). In each case, the polarity of the voltage induced is different, as shown.

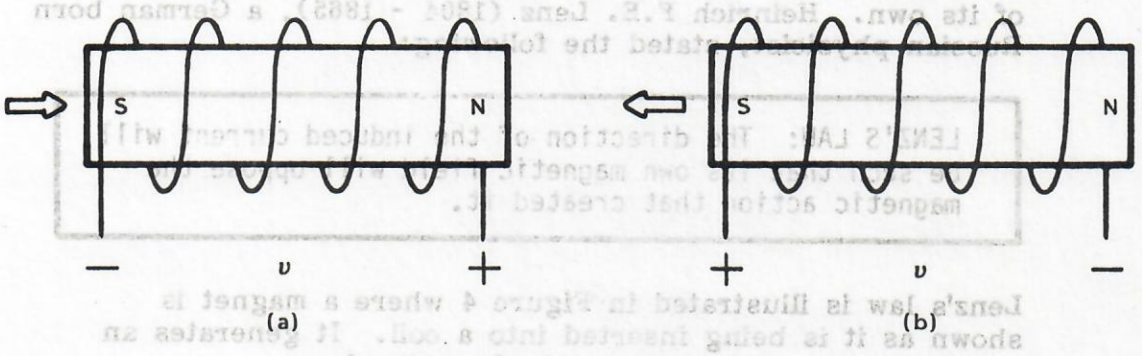


Figure 3(a) - Output polarity when the magnet is inserted into the coil and (b), removed from the coil.

The amplitude of the voltages generated in Figures 3(a) and (b) are determined by how fast the magnet is moved as explained earlier and by the strength of the magnetic field ($\Delta\Phi/\Delta t$).

As an example, consider an electromagnet that generates a magnetic flux of 0.15 webers. A 300 turn coil is moved through the field in 1/2 second. The induced voltage in the 300 turn coil is determined from:

$$v = N\frac{\Delta \Phi}{\Delta t}$$

where $N = 300$ turns
$\Delta\Phi = 0.15$ webers
$\Delta t = 0.5$ seconds

The instantaneous induced voltage is:

$$v = 300\ \frac{0.15}{0.5}$$

$$\boxed{v = 90 \text{ volts}}$$

INDUCED CURRENT

When a complete circuit is connected across the coil as shown in Figure 4, an induced voltage will cause a current flow. This happens because the electrons that are forced to one end of the coil flow through the external circuit to the other end of the coil that is missing the electrons and then flow through the coil also.

The magnetic field cutting the coil is causing a current in the coil. But now the induced current is flowing through the coil and this current generates another magnetic field of its own. Heinrich F.E. Lenz (1804 - 1865), a German born Russian physicist, stated the following:

> LENZ'S LAW: The direction of the induced current will be such that its own magnetic field will oppose the magnetic action that created it.

Lenz's law is illustrated in Figure 4 where a magnet is shown as it is being inserted into a coil. It generates an induced current that causes the lamp to glow.

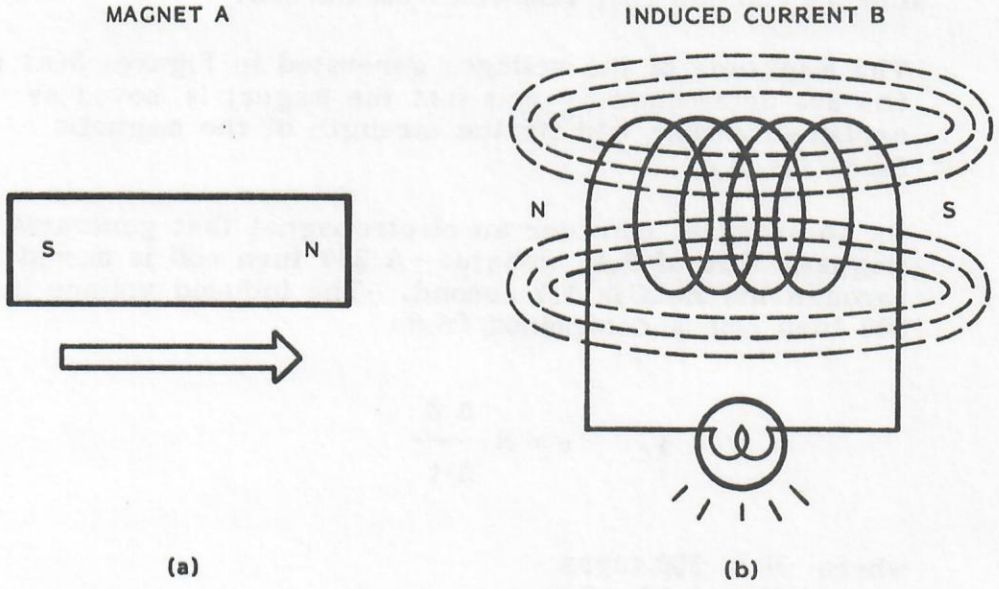


Figure 4 - Induced current caused by magnet A creates electromagnet B.

The generated magnetic field is opposite to the applied field as shown above, Figure 4(b). This new magnetic field resists the insertion of magnet A because like poles repel. It is actually this recognition of Lenz's law that lets us predict the direction of induced current flow.

Thus, if we force a magnet into a coil that has a complete circuit across it to conduct current, we will experience a resisting physical force. The greater the current flow, the greater will be the resisting force. If we rotate an electric generator, we will find it harder to turn when there is a greater electrical load on it.

CONCLUSIONS

We have learned from this information sheet that:

When a magnetic field cuts across a wire a voltage is developed across that wire.

The voltage generated can be increased by forming the wire into a coil.

The voltage induced in a coil is a function of the magnetic field strength, the speed of movement of the field or coil and the number of turns on the coil.

The above statement summarizes Faraday's Law and can be shown as:

$$v_{IND} = N\frac{\Delta \Phi}{\Delta t}$$

The faster the movement of the magnetic field, the greater the induced voltage.

Lenz's law states that when an induced current flows through a coil, a magnetic field polarity is generated that opposes the generating field.

ASSIGNMENT

Answer the following True-False questions.

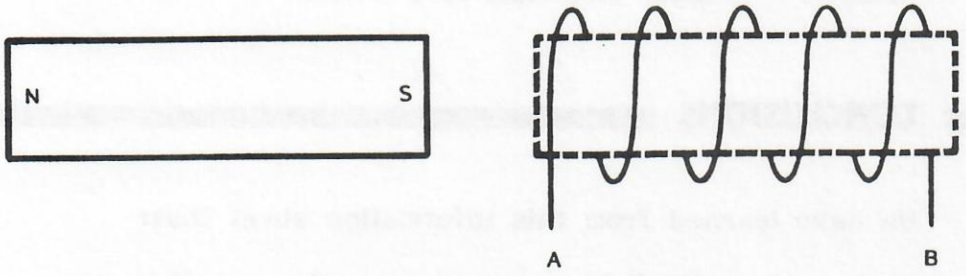


Figure 5 refers to questions 1 to 5.

1. When the bar magnet in Figure 5 is inserted into the coil shown, a current will be developed between A and B. ____

2. The polarity between A and B in Figure 5, when the magnet is inserted into the coil will be A+, B-. ____

3. When the magnet in Figure 5 is withdrawn from the coil no voltage will be generated. ____

4. The amplitude of the voltage generated by the magnet in Figure 5 is a function of the speed of movement. ____

5. An induced voltage in Figure 5 is present only when the magnetic field or the coil is in movement. ____

6. Faraday's law states that the induced voltage is equal to $(N)(d\Phi/dt)$ where d = delta. ____

7. Faraday's law allows the determination of the polarity of the induced voltage across a coil. ____

8. Lenz's law states that the polarity of the induced voltage will cause a current flow that will oppose the change in magnetic flux causing the induced voltage. ____

9. The more rapid the change in flux through a coil the greater the induced voltage. ____

10. If the flux cutting across a coil does not change, but remains constant, the output voltage remains constant. ____

KEY TERMS

1. COLLAPSING MAGNETIC FIELD

   The shrinking inward of a magnetic field when the current flowing through the coil is reduced or cut off.

2. EXPANDING MAGNETIC FIELD

   The outward movement of a magnetic field when the current flowing through the coil is increased.

3. FARADAY'S LAW

   The voltage generated across a coil of wire by a magnetic flux is directly proportional to the number of turns of wire in the coil, the strength of the magnetic field and the speed of movement of the magnetic field or coil.

4. INDUCTION

   The creation of a voltage and current flow in a conductor by a moving (varying) magnetic field.

5. LENZ'S LAW

   An induced current flow will create a magnetic field that opposes the magnetic field that created it.

6. STATIONARY MAGNETIC FIELD

   A magnetic field that is not increasing or decreasing in strength or moving physically.

Electromagnetic Voltage Induction 6

OBJECTIVES

When you finish this experiment, you will be able to:

1. Induce a voltage in a hand wound coil using a bar magnet.
2. Increase the number of turns by using a relay coil and observe the effect on the induced voltage and current.
3. Observe the effect of magnetic polarity on the induced voltage polarity.
4. Observe the effect of direction of magnetic movement on the induced voltage polarity.
5. Observe the effect of speed of magnetic movement on the strength of the induced voltage.

REFERENCE

Information Sheet 4, Electromagnetic Induction

ADDITIONAL EQUIPMENT

a. Relay Plug-in Card CES 318 or equal (optional)
b. Coil with 35 turns or 30' length of insulated wire.
c. Bar Magnet
d. 2 Banana to Alligator Clip Adaptors

DESCRIPTION

The purpose of this experiment is to verify some of the principles of magnetic induction explained in Information Sheet 4 and listed in the Objectives above.

Magnetic induction will first be demonstrated using a hand wound coil with approximately 35 turns. It will then be demonstrated using the relay coil which has many more turns and therefore can develop a greater induced voltage.

This experiment may best be performed as a demonstration by the instructor.

PROCEDURE

1. Wind the 30' length of hookup wire in a tight coil leaving the center opening of the winding large enough to pass the bar magnet, or use a pre-wound coil.

2. Connect the coil to the 50 μA input jacks of the meter, as shown in Figure 1, using banana to alligator clip adaptors.

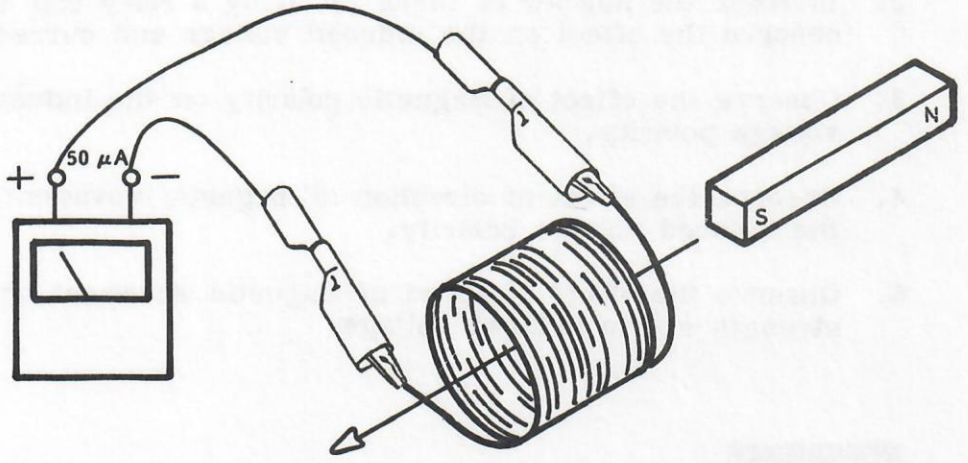


Figure 1 - Set-up to demonstrate magnetic induction; EXPERIMENT.

6.1 INDUCED VOLTAGE AND POLARITY

3. Plunge the S pole of the magnet into the coil center as quickly as possible and observe the direction of deflection or movement of the meter pointer.

   In what direction and how many divisions did the meter pointer move when the S pole was thrust into the coil?

   _____

   _____

4. Quickly remove the S pole from the coil center while observing the direction of the meter pointer movement.

   In what direction did the meter pointer move when the S pole was removed from the coil?

   _____

   _____

   What is the effect on the induced voltage and current of reversing the direction of movement of the magnetic field?

   _____

   _____

5. With the bar magnet reversed, that is, with the N pole being plunged into and removed from the coil, repeat steps 3 and 4.

What effect does the reversal of the magnetic polarity have on the induced voltage?

6.2 PARALLEL LINES OF FLUX

6. Swing the N or S pole of the bar magnet parallel to the coil as shown in Figure 2.

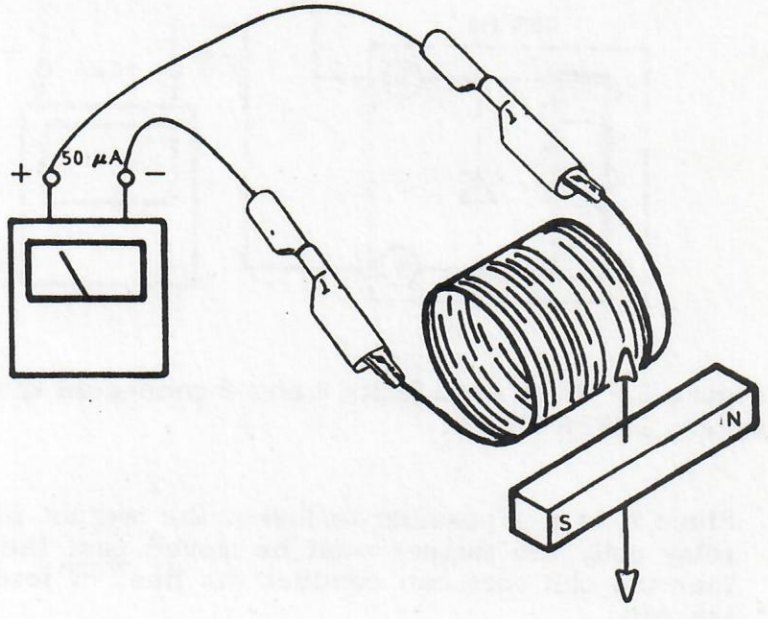


Figure 2 - Lines of force moving parallel to the coil; EXPERIMENT.

How does moving the magnet parallel to the coil affect the induced voltage?

6.3 RELAY COIL (OPTIONAL)

7. The electromagnet used for the relay coil has 5800 turns of wire wound on a soft iron core. Because of the core construction and enclosure it is not possible to plunge a magnet into its center and so a direct comparison to the hand wound core is not possible. It will be observed, however, that the increased number of coil turns increases the induced voltage greatly. This increase occurs even though the magnet can only be swept past the coil but not through it.

8. Plug the Relay Card into the PC socket on the Ed-Lab panel with the pin 1 marking on the left. Wire the circuit shown in Figure 3.

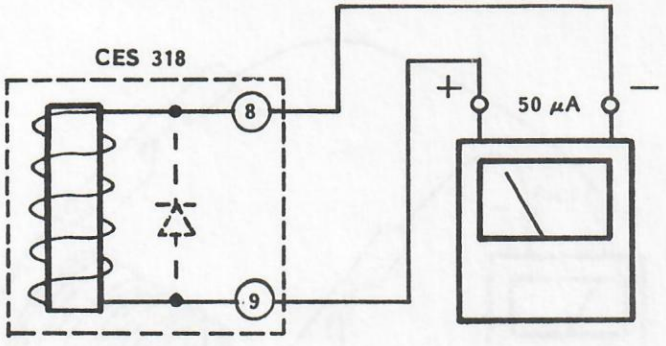


Figure 3 - Relay card jacks 8 and 9 connected to the 50 μA meter; EXPERIMENT.

9. Since it is not possible to insert the magnet into the relay coil, the magnet must be moved past the coil so that the coil core can conduct the lines of force into the coil.

   Move the bar magnet across the end of the relay coil as shown in Figure 4 and observe the meter pointer action.

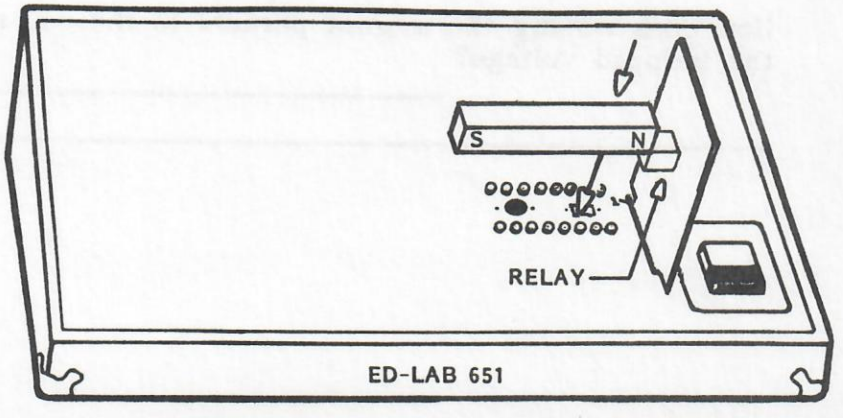


Figure 4 - Inducing voltage into the relay coil.

How does the strength of the voltage induced compare to the hand wound coil used in steps 1 to 6? _____

_____

_____

What happens to the polarity of the induced voltage after the magnet moves past the center of the electromagnet? _____

_____

10. Move the magnet past the coil as slowly as possible.

    How does the reduce speed affect the induced voltage? _____

    _____

    _____

11. Reverse the magnet polarity and repeat the procedure using the S pole.

    How do the results differ? _____

    _____

12. Place the N end of the magnet against the end of the relay case but do not introduce any further movement.

    What effect does lack of movement have on the induced voltage? _____

    _____

CONCLUSIONS

We have learned from this experiment that:

The direction of movement of the magnetic field determines the polarity of the induced voltage.

The magnetic lines of force induce the most voltage when perpendicular to the coil winding.

Increasing the number of coil turns increase the output voltage.

The greater the speed of movement of the magnetic field the greater the induced voltage.

If there is no movement there is no induced voltage.

ASSIGNMENT

Answer the following True False questions.

1. The induced voltage in a coil sitting in a stationary magnetic field is determined by the field strength and number of turns. _____

2. Reversing the direction of movement of the magnetic field reverses the polarity of the induced voltage. _____

3. The induced voltage would double if the number of flux lines were doubled. _____

4. The induced voltage would be four times greater if the magnetic field strength doubled and the number of turns were reduced by half on the coil. _____

5. The induced voltage will increase as the speed of movement of the magnetic field is increased. _____

6. A magnetic field cannot exist if there is no motion. _____

KEY TERMS

1. COLLAPSING MAGNETIC FIELD

   The shrinking inward of a magnetic field when the current flowing through the coil is reduced or cut off.

2. EXPANDING MAGNETIC FIELD

   The outward movement of a magnetic field when the current flowing through the coil is increased.

3. FARADAY'S LAW

   The voltage generated across a coil of wire by a magnetic flux is directly proportional to the number of turns of wire in the coil, the strength of the magnetic field and the speed of movement of the magnetic field or coil.

4. INDUCTION

   The creation of a voltage and current flow in a conductor by a moving (varying) magnetic field.

5. LENZ'S LAW

   An induced current flow will create a magnetic field that opposes the magnetic field that created it.

6. STATIONARY MAGNETIC FIELD

   A magnetic field that is not increasing or decreasing in strength or moving physically.

DC Motors and Generators

INFO SHEET 4

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Explain the operation of a permanent magnet dc motor.
2. Describe the basic construction of the armature and commutator of the dc motor.
3. Define what is meant by a Counter EMF and explain how it affects the motor current drain.
4. List and define the various motor rating criteria such as Torque, RPM, Horsepower and Efficiency.
5. Explain the operation of a dc permanent magnet type generator.
6. Draw the circuit of a resistive starter device for a motor.
7. List and explain the factors that affect the output voltage of a dc permanent magnet generator.
8. Calculate the output voltage of a dc generator.
9. Define what is meant by ripple in the dc generator output.
10. Explain the effect of generator loading.
11. Explain the use made of motor-generator sets.

DISCUSSION

The purpose of a motor is to convert electrical energy to mechanical energy. The purpose of a generator is the reverse, to convert mechanical energy to electrical energy.

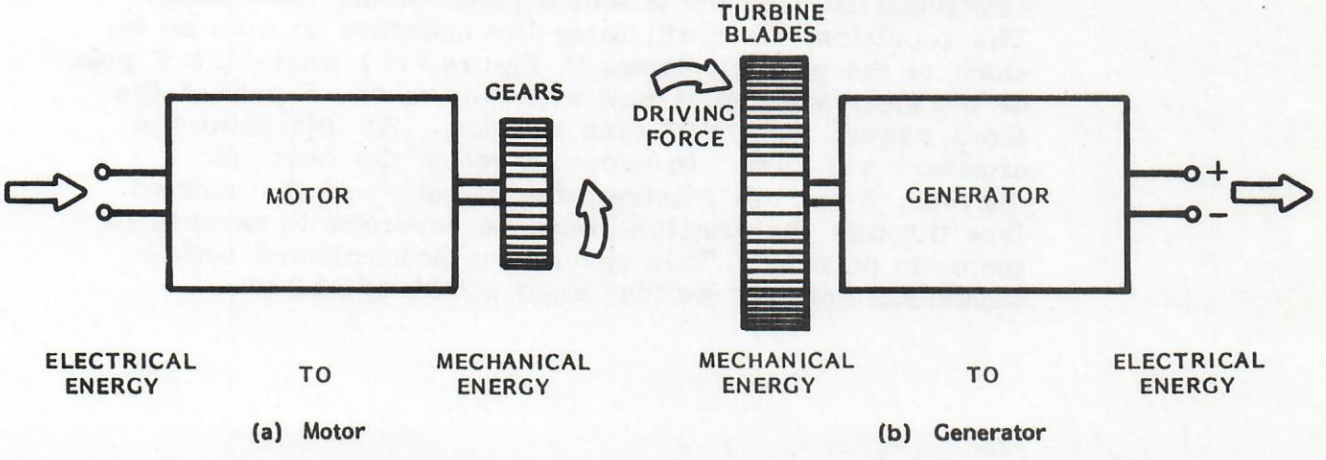
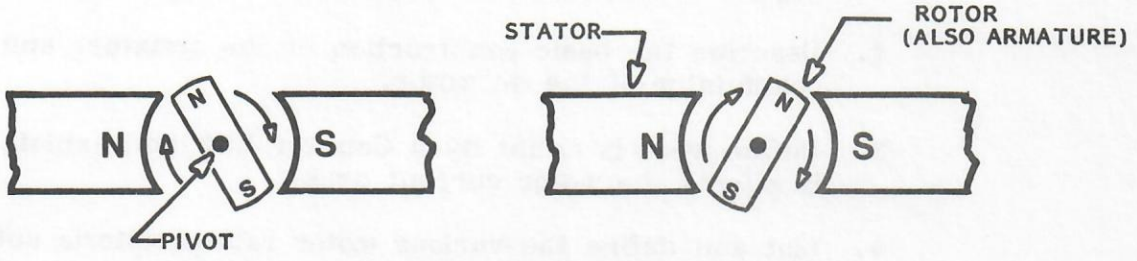


Figure 1 - Conversion of electrical to mechanical energy by a motor (a) and mechanical to electrical energy by a generator (b).

The basic operating principle of a motor is the mechanical force of attraction and repulsion resulting from magnets in close proximity to each other. One magnet is held stationary and the other is pivoted as shown in Figure 2.



(a) Twisting force due to repulsion.

(b) Twisting force due to attraction.

Figure 2 - Magnetic principle of motor action.

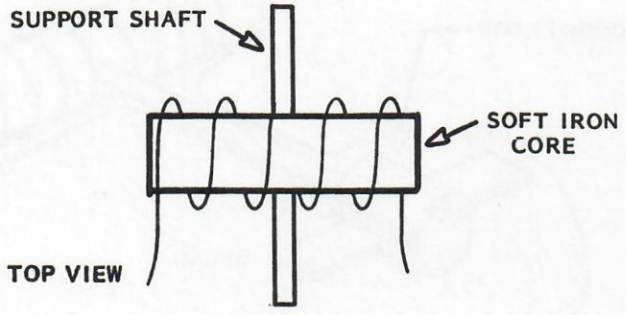
The stationary part of the motor is called the STATOR and the rotating part is called the ROTOR or ARMATURE.

The rotor portion of the motor is not a permanent magnet; it is an electromagnet as shown in Figure 3 (b) and (c). The electromagnet is positioned between the N and S pole of the fixed magnets called FIELD MAGNETS.

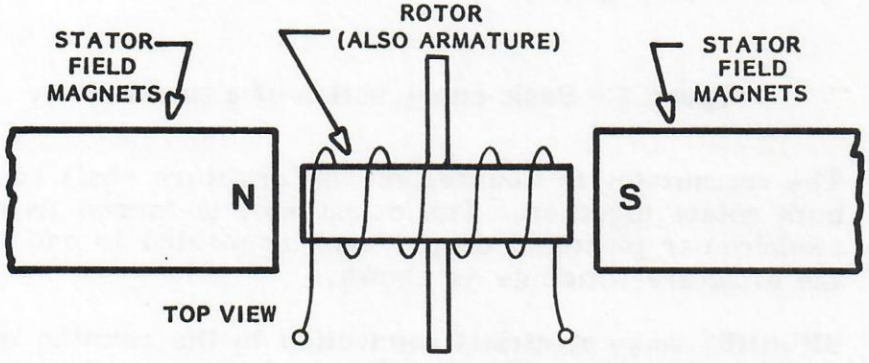
The rotating magnetic field is created by the ARMATURE winding shown in Figure 3(b). The armature is placed in the fixed field as shown in Figure 3(c). When the armature winding is connected to a source of dc voltage and current, an electromagnetic field is created as shown in (a) of Figure 4.

Application of the Left Hand Rule (Information Sheet 2, Electromagnets) indicates that the N and S poles of the electromagnet face the N and S poles of the fixed field. The repulsion effect will force the armature to turn on its shaft to the position shown in Figure 4(b) where the N pole of the electromagnet is now attracted to the S pole of the fixed magnet for a half turn rotation. At this point the armature will stop. In order to rotate the next 180 degrees, for a full rotation, the direction of the current flow through the armature must be reversed to reverse its magnetic polarity. This reversal is accomplished with a mechanical rotating switch called a COMMUTATOR.

(a) Fixed magnetic field.



(b) Rotating electromagnet (armature)



(c) Armature placed in fixed magentic field.

Figure 3(a) - Fixed magnetic field. (b) - Armature electromagnet. (c) - Armature placed in fixed field.

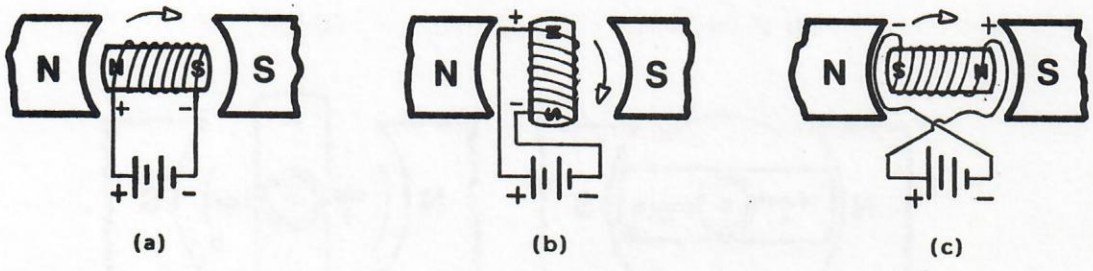


Figure 4 - Armature rotation of 180 degrees.

COMMUTATOR

The device used to reverse the polarity of the voltage applied to the armature is called a COMMUTATOR and its construction is shown in Figure 5.

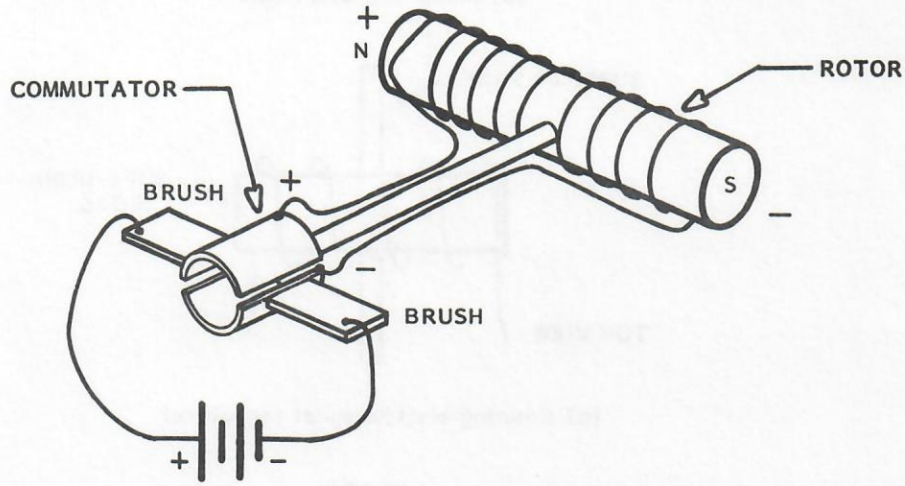


Figure 5 - Basic construction of a commutator.

The commutator is mounted on the armature shaft so that they both rotate together. The commutator is formed from two semicircular pieces of copper each connected to one end of the armature windings as shown.

BRUSHES make electrical connection to the rotating commutator and, after a 180 degree movement of the armature, reverse the current flow direction to obtain the second 180 degree rotation. How this is done is illustrated in Figure 6.

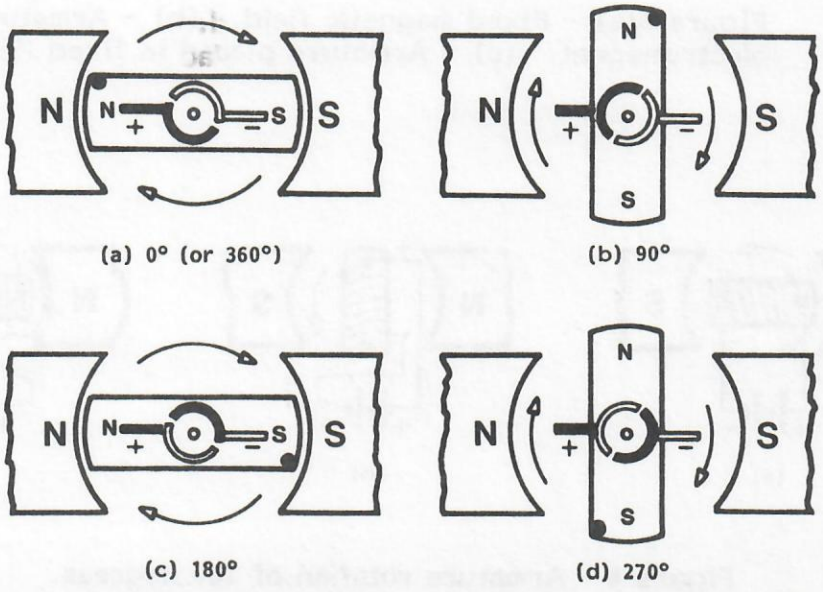


Figure 6 - Steps in the 360 degree rotation of the armature.

In (a) of Figure 6 the dc voltage source is connected to the armature winding through the brushes creating an electromagnetic field with the polarity shown. Because like poles repel the armature rotates 90 degrees to the position shown in (b). The brushes still are contacting the same segments of the commutator and so the polarities of the applied voltage and the magnetic poles remain the same.

In the position shown in (b) of Figure 6, the N pole of the armature is now attracted to the S pole of the permanent magnet and the S pole of the armature to the N pole of the permanent magnet. This causes the armature to turn a second 90 degrees to the position shown in (c). A close look at the commutator in (c) shows that the brushes will now be in contact with different sections of the commutator thus reversing the polarity of the applied voltage to the armature. This results, as shown, in a reversal of the armature polarity and again there is a repulsion effect shifting the armature another 90 degrees to the position shown in (d) of Figure 6. The N pole of the armature will now be attracted to the S pole of the permanent magnet (not shown in Figure 6) to complete a 360 degree rotation which will continue, thus rotating the armature shaft.

Motors with two section commutators are not normally built because they are not self-starting. It requires three or more commutator sections to have a self-starting motor. In actual motors there are many armature windings and commutator segments. Also, the forces between the stator and rotor that turn the motor armature are not constant as shown in Figure 7.

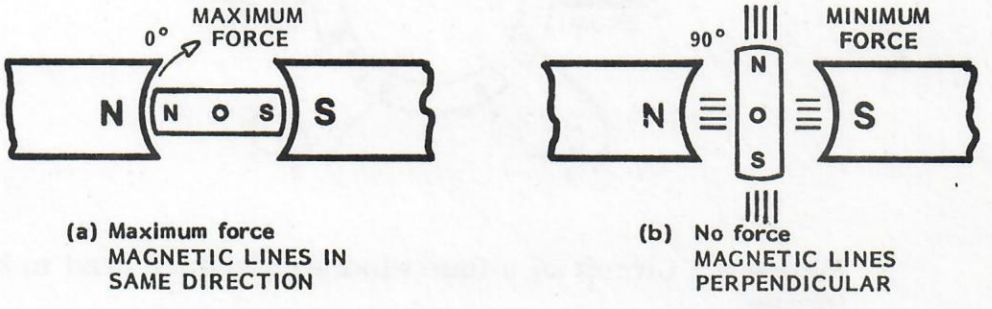


Figure 7 - Armature position for maximum and minimum forces.

If we were to plot rotor force against the degree of rotation, the result will be as shown in Figure 8.

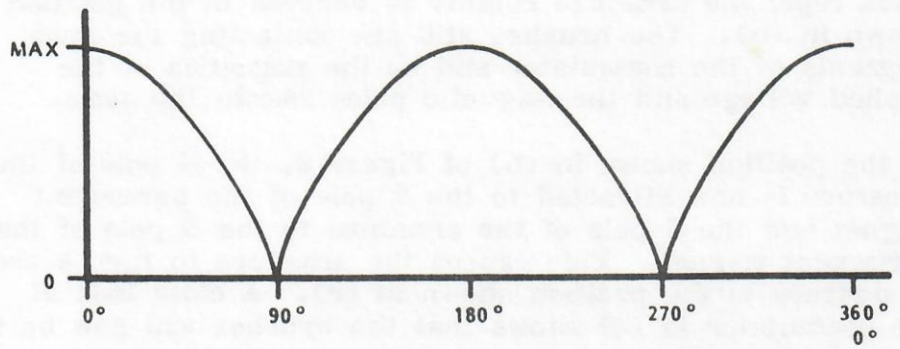


Figure 8 - Motor rotor force versus angle of rotation.

To develop stronger and more constant rotational force an armature is constructed with more than one winding as shown in Figure 9. The use of four windings requires the commutator to be divided into four segments, as shown, rather than two.

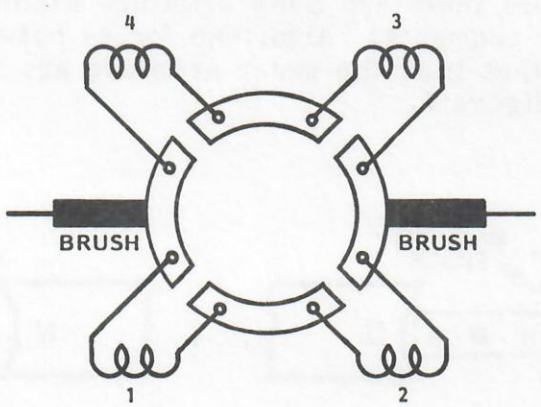


Figure 9 - Circuit of a four winding armature used to improve torque.

The rotational forces are increased greatly because all four of the armature windings are energized at the same time. Windings 1 and 2 are in series as are 3 and 4 and both series windings are in parallel. Not only is the rotational force increased but it is more constant as it never drops to a zero

level. The rotating forces may be further improved by the use of armatures with up to 12 or more windings. The resultant force with additional windings is shown in Figure 10.

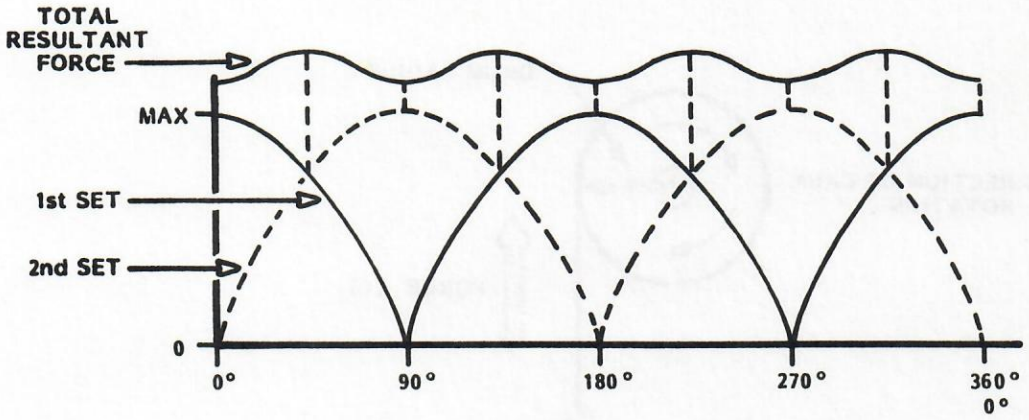


Figure 10 - Total resultant rotor force with two sets of coils in the armature.

FORCES AND TORQUE

The forces acting on the conductors in the armature of the motor are determined by:

a. L - the length of the conductor in the field (in inches)

b. B - the strength (flux density) of the magnetic field (lines per in^2)

c. I - the current flow in the conductors (amperes)

d. N - the number of turns in the winding

The equation for Force (F), in pounds is:

$$F = \frac{8.85\ NBLI}{10^8}$$

The "rotational force" or "twisting force" developed by the motor shaft is called TORQUE (pronounced "tork") and is illustrated below in Figure 11.

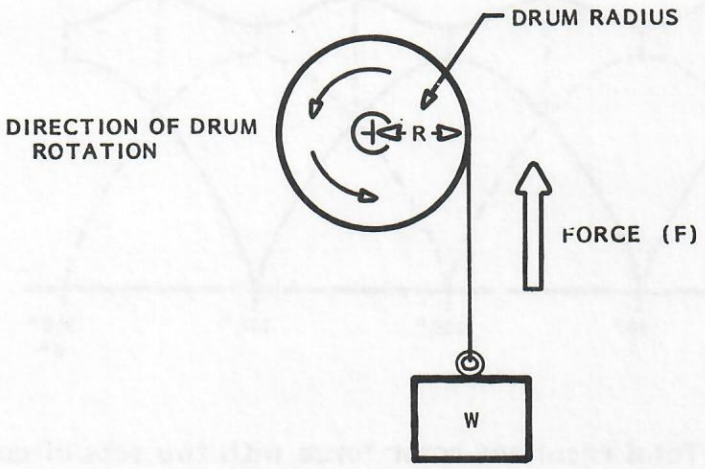


Figure 11 - Torque or rotational force.

The torque developed is given by the equation

$$T = FR$$

where T = Torque in Foot-Pounds
F = Force in Pounds
R = Radius in Feet

If the force or weight to be pulled is 12 pounds and the radius is 6 inches (0.5 feet), the torque required to lift the weight is

$$T = FR$$

$$= (12 \text{ lbs})(0.5 \text{ inch})$$

$$= 6 \text{ Ft-Lbs}$$

To illustrate this further, consider a motor with the following construction details:

Flux Density, B = 56,465 lines in^2
Armature Current, I = 1.895 A
Armature Conductor Length, L = 8"
Armature Radius, R = 4" (0.33 feet)
Conductors in Field, N = 30

The torque is then given by:

$$T = FR$$

Substituting for F, we have

$$T = \frac{8.85\ NBLI\ (R)}{10^8}$$

$$= \frac{(8.85)(30)(56,465)(8)(1.895)(0.33)}{10^8}$$

TORQUE = 0.75 FOOT-POUNDS

MOTOR RATINGS

Motors are rated by their voltage, current drain, speed of rotation, output power and if the required input voltage is AC or DC. These are further described below.

MOTOR SPEED

Motor speed is the measure of number of rotations of the armature shaft in one minute and is called Revolutions Per Minute. This is abbreviated as RPM. A typical speed may be 1750 RPM.

HORSEPOWER

The rate at which a motor can perform work is called HORSEPOWER and is abbreviated as HP. The horsepower delivered by a motor depends upon the FORCE or TORQUE and its speed or RPM and is given by the following equation.

$$\text{HORSEPOWER (HP)} = (0.00019)(\text{TORQUE})(\text{RPM})$$

With the torque of 0.75 ft-lbs calculated earlier and an assumed speed of 1750 RPM, the horsepower rating of a motor is:

$$HP = (0.00019)(0.75)(1750)$$

$$\text{HORSEPOWER} = \underline{0.2494} = \underline{1/4\ HP}$$

A 1/4 horsepower motor, often referred to as a fractional horsepower motor, is a commonly used size for many household appliances and small power tools.

CURRENT DRAIN AND COUNTER EMF

The electrical winding in the armature may have a total resistance of 10 ohms. If the voltage applied to the motor is 120 volts, then the current, according to Ohm's Law, will be:

$$I = \frac{E}{R}$$

$$= \frac{120}{10}$$

$$I = 12 \text{ amperes}$$

As described earlier, however, when a coil rotates in a magnetic field a voltage is induced in the coil which is opposite in direction and opposes the applied voltage (Lenz's Law). This induced voltage is called the COUNTER EMF or CEMF. As a result, the final current is actually less than that calculated by Ohm's Law. One example is shown below in Figure 12.

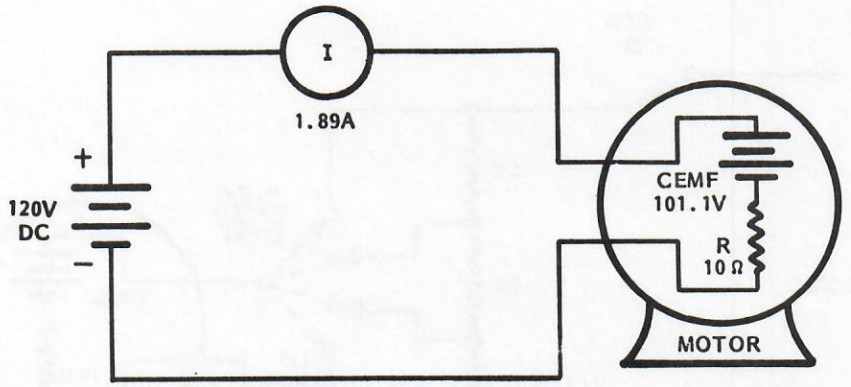


Figure 12 - CEMF of 101.1 volts reduces motor current from 12 amperes to 1.89 amperes.

CURRENT DRAIN AND LOAD

The motor current drain, as just explained, is affected by the following:

a. The applied voltage
b. Motor armature resistance
c. The Counter EMF

The CEMF, however, is determined by the speed of the rotation. As the load or weight driven by the motor increases, the motor speed decreases. The decrease in speed reduces the CEMF thus increasing the current drain. The armature power dissipation (I^2R) is increased and the motor will heat up. The motor may overheat or blow the protective fuse.

As the motor load is increased, the current drain is increased, the heat losses are increased, and the speed is decreased.

RESISTANCE STARTER

When starting, the motor has no speed and the full high current (12 A in our example) can blow a fuse. As a result, for high power motors, we must insert a resistor in series with the line before starting the motor and gradually reduce the resistance as the motor starts to speed up. Such a unit is called a MOTOR STARTER and is shown in Figure 13.

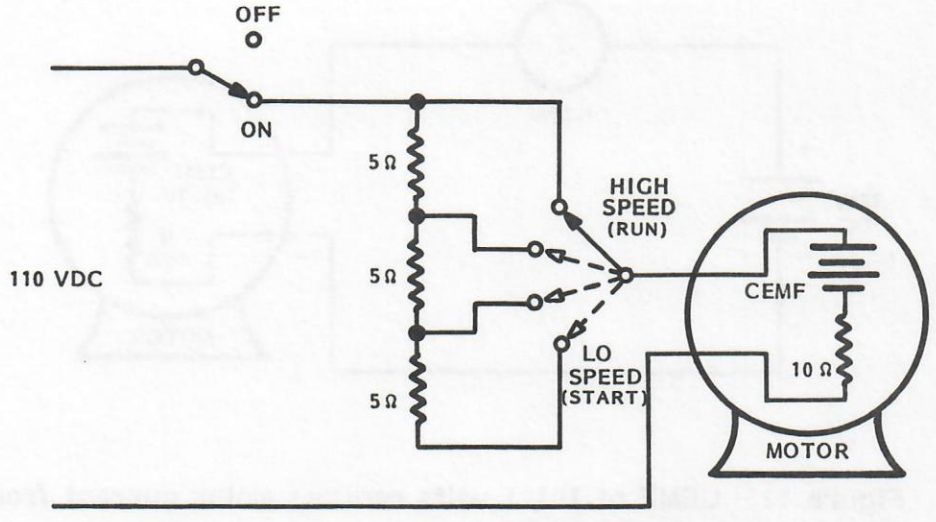


Figure 13 – Motor Starter circuit for high power motors.

EFFICIENCY

The motor provides mechanical output power measured in HORSEPOWER (1/4 HP for our example). From Information Sheet 8, Unit E3, Mechanical Energy Conversions, we have

$$1 \text{ HP} = 746 \text{ Watts}$$

Therefore:

$$\text{MECHANICAL OUTPUT POWER} = (\text{HP})(746 \text{ W})$$

$$= \left(\frac{1}{4}\right)(746)$$

MECHANICAL OUTPUT POWER = 186.5 Watts

(Equivalent for 1/4 HP motor)

The input to the motor, when running, was noted earlier as 1.89 amperes at 120 volts. The input power, therefore, is:

$$\text{ELECTRICAL INPUT POWER} = E \cdot I$$

$$= 120 \times 1.89$$

$$\boxed{\text{ELECTRICAL INPUT POWER} = \underline{226.8 \text{ Watts}}}$$

Energy and power are lost in heat in the armature resistance (I^2R) and a small amount of power is given up in "rotational losses" such as friction and wind resistance.

The EFFICIENCY of the motor is a percentage of the ratio of the output power to the input power and is expressed as:

$$\text{PERCENTAGE (\%) EFFICIENCY} = \frac{P_{OUT}}{P_{IN}} \times 100\%$$

The efficiency of the motor in our example is:

$$\% \text{ EFFICIENCY} = \frac{186.5}{226.8} \times 100$$

$$\boxed{\% \text{ EFFICIENCY} = \underline{82.2\%}}$$

The total power loss due to inefficiencies is:

$$P_{LOSS} = P_{IN} - P_{OUT}$$

$$= 226.8 - 186.5$$

$$P_{LOSS} = 40.3 \text{ Watts}$$

The copper (I^2R) losses are

$$P_{LOSS} = I^2R$$

$$= (1.89)^2\ 10$$

COPPER LOSSES P = 35.72 W

The remaining losses are equal to:

$$40.3\ W - 35.72\ W = 4.58\ W$$

Thus friction and windage losses are 4.58 W for a total loss of 40.3 watts.

FIELD WINDINGS

In order for the armature of a motor to turn when current flows through its armature winding, it must work against a fixed magnetic field. In small motors, the magnetic field is provided by permanent magnets and are thus called PM Motors. In larger motors, 1/4 HP and greater, the magnetic field strength required is often too great to be supplied by most types of permanent magnets. As a result, the magnetic field required for the armature to work against must be provided by an electromagnet. This additional winding is called a FIELD COIL and is shown in Figure 14 in various forms.

In Figure 14(a) the field is wired in series with the armature and is known as a SERIES motor. In (b) the field is in parallel with the armature and is known as a SHUNT type motor. Large motors are often wound with both a Series and Shunt field and are called COMPOUND motors.

In many instances the motor circuit is not drawn but simply represented by the symbol shown in Figure 14(d).

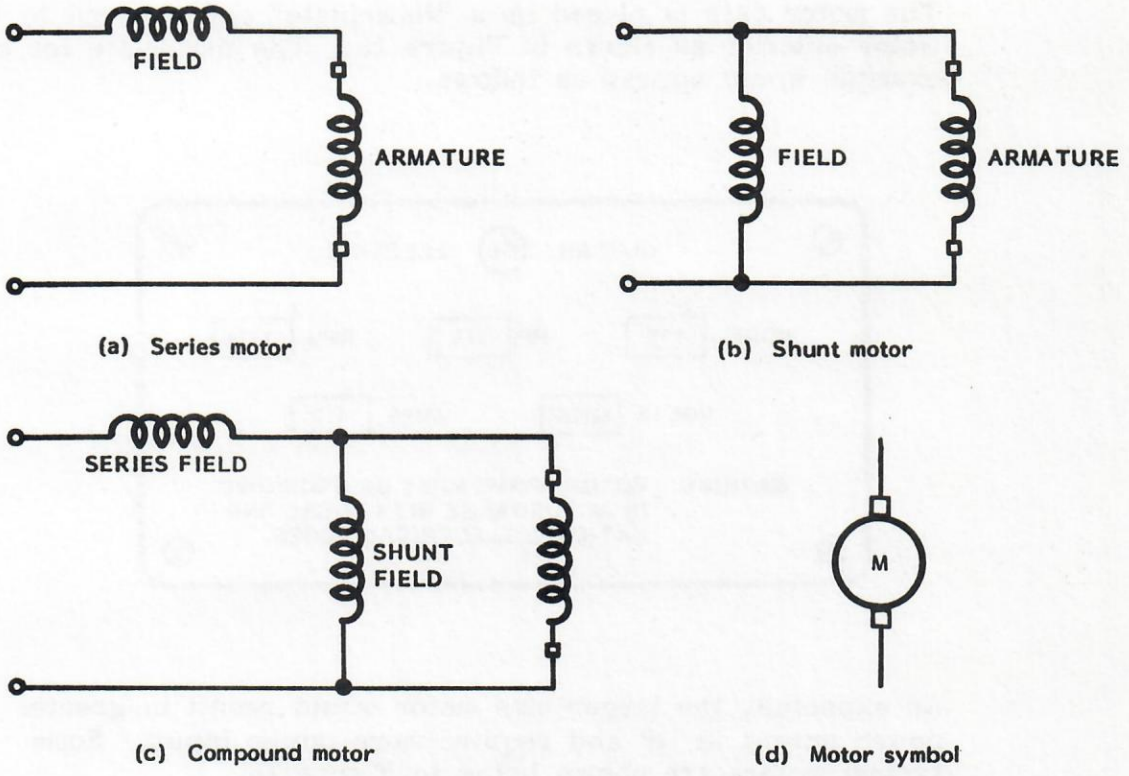
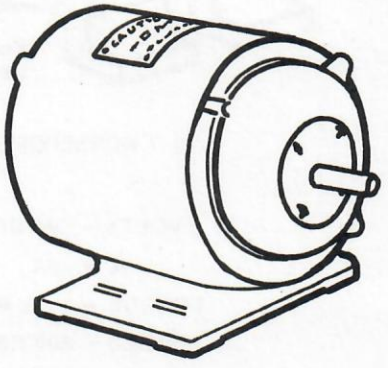


Figure 14(a) - Series field motor. (b) - Shunt field motor. (c) - Compound motor. (d) - Motor symbol.

MOTOR SUMMARY and NAMEPLATE

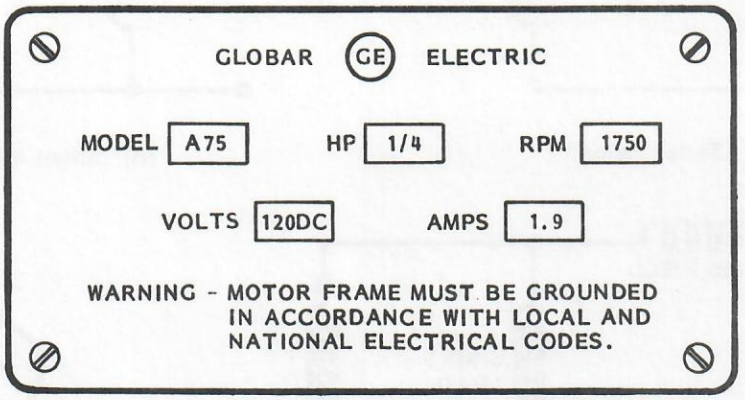
The characteristics of a typical 1/4 horsepower motor are summarized in Figure 15 below.



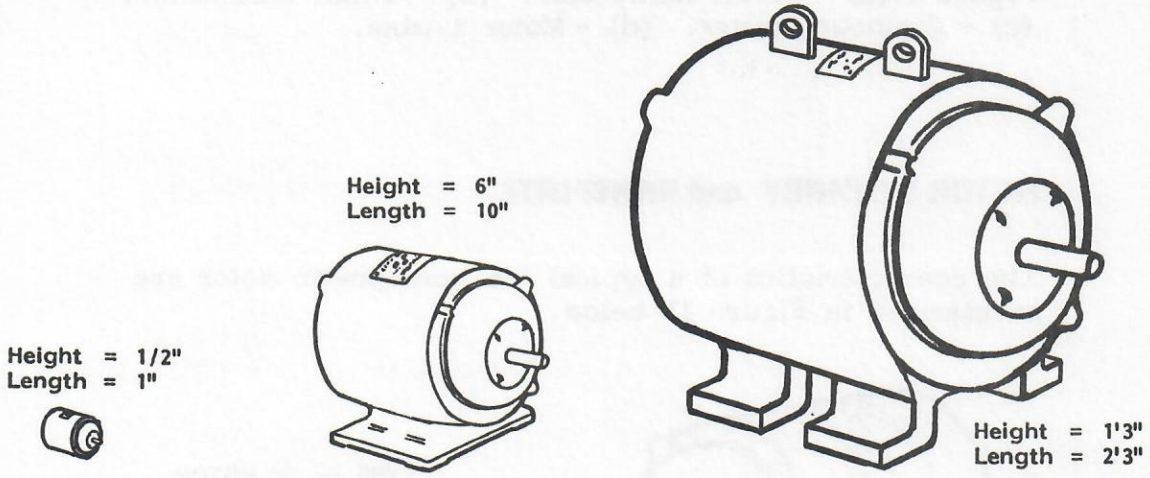
TYPE — DC MOTOR
VOLTAGE — 120V
CURRENT — 1.9A
HP — 1/4
TORQUE — 0.75 ft-lbs.
EFFICIENCY — 82%
RPM — 1750

Figure 15 - Summary of the motor used in the text example.

The motor data is placed on a "Nameplate" and secured to the motor exterior as shown in Figure 15. The nameplate for our example would appear as follows.


GLOBAR GE ELECTRIC
MODEL A75
HP 1/4
RPM 1750
VOLTS 120DC
AMPS 1.9
WARNING - MOTOR FRAME MUST BE GROUNDED IN ACCORDANCE WITH LOCAL AND NATIONAL ELECTRICAL CODES.

As expected, the larger size motor would result in greater power output in HP and require more power input. Some typical motors are shown below in Figure 16.



(a) CONTROL MOTOR	(b) FRACTIONAL HP MOTOR - 3/4 HP	(c) 2 HORSEPOWER
VOLTS – 12 DC	VOLTS – 120 DC	VOLTS – 220 DC
I – 100 mA	I – 5.7 A	I – 20A
TORQUE – 12 oz-inches	TORQUE – 2.25 ft-lbs	TORQUE – 14 ft-lbs
SPEED – 10,000 RPM	SPEED – 1750 RPM	SPEED – 800 RPM
PM FIELD MAGNETS	FIELD WINDINGS	COMPOUND FIELD WINDINGS

Figure 16 - Typical motors of different HP ratings.

GENERATORS

The purpose of a GENERATOR is to convert mechanical energy into electrical energy. Most generators are rotary magnetic devices and so our discussion will be confined to that type. The motor just studied performed the opposite function; it converted electrical to mechanical rotational energy. This difference in principle between motors and generators is illustrated in Figure 17.

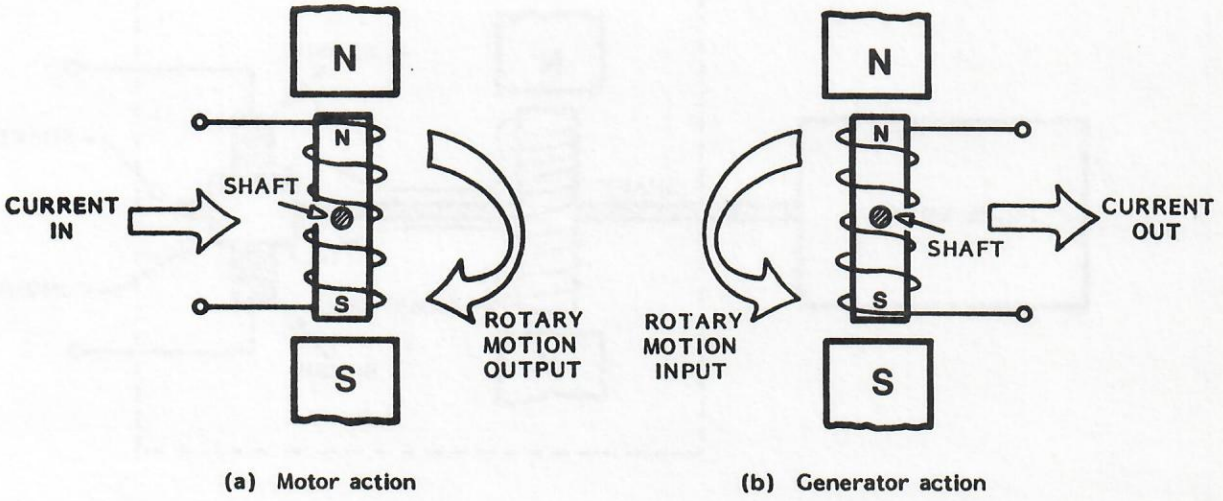


Figure 17 - Comparison of the motor and generator action.

The symbols for the motor and generator are also similar as shown in Figure 18 below. The dashed lines shown indicated a mechanical connection, that is, the rotor shaft.

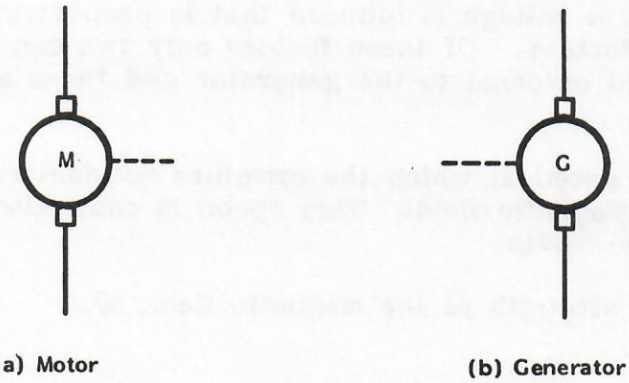


Figure 18 - Motor and generator symbols.

The construction of the dc motor and generator are the same. The generator shaft is driven by a source called the "prime mover" which can be a motor or a steam or water driven turbine. The construction and operation is as shown below in Figure 19.

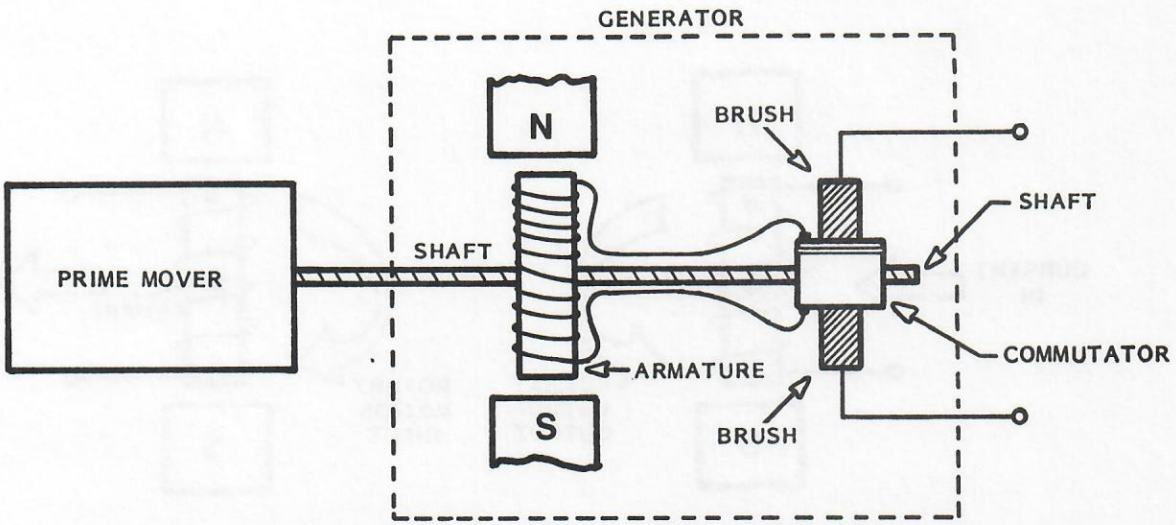


Figure 19 - Construction of a basic generator.

GENERATOR OUTPUT VOLTAGE

As the prime mover drives the generator shaft, the armature is rotated in the magnetic field produced by the N-S poles of the permanent magnet. When the armature cuts the lines of force, a voltage is induced that is proportional to several factors. Of these factors only two can be controlled external to the generator and these are:

1. The speed at which the armature conductors move through the magnetic field. This speed is controlled by the prime mover.

2. The strength of the magnetic field, Ø.

If the magnetic field is created by a permanent magnet, the field strength cannot be varied and so only factor 1 above will control the output voltage. If the magnetic field is

created by an electromagnet, then the field strength can be varied by control of the winding current. This will result in control of the output voltage as shown in Figure 20.

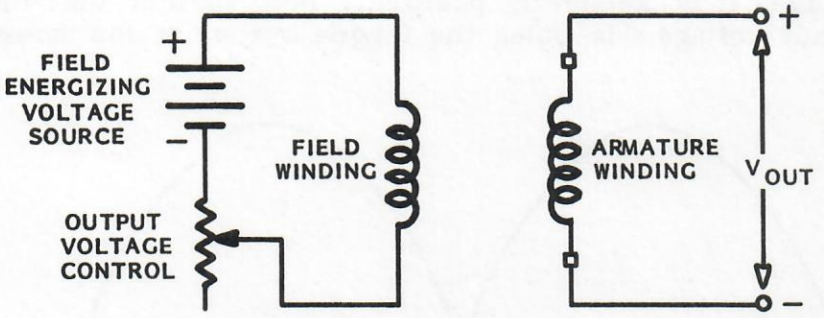


Figure 20 - Output voltage control by adjusting the current flow in the field winding of the generator.

The output voltage V_O for a given generator may be calculated from

$$V_O = K \Phi S$$

where Φ = number of lines in the magnetic field
S = speed of the armature rotation in RPM
K = the fixed factors in the generator such as the total number of conductors on the armature, the number of parallel paths on the armature winding and so on.

If, for a specific generator, the value of K is 6×10^{-8}, the prime mover is rotating at 800 rpm and the magnetic field strength is 6×10^6 lines, the output voltage is

$$V_O = K \Phi S$$

$$= (6 \times 10^{-8})(800)(6 \times 10^6) = \underline{288\ V}$$

GENERATOR OUTPUT WAVEFORM

The output voltage generated by the simple dc generator of Figure 19 is shown below in Figure 21. Note that for a single rotation of the armature, 360 degrees, the output consists of two pulses of voltage. While not a steady voltage, it is constantly positive. Note further that the output voltage resembles the torque output of the motor.

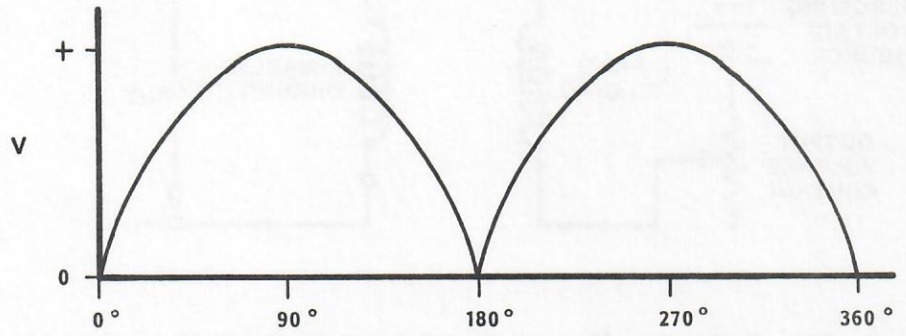
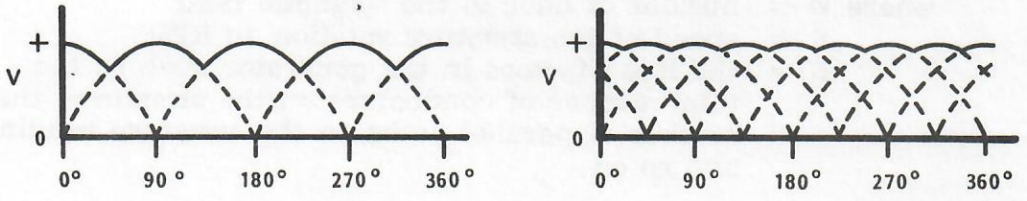


Figure 21 - Output voltage for one rotation of the generator armature.

To provide a more constant output voltage the number of armature windings are increased. A two coil generator would produce an output voltage as shown in Figure 22(a) while a three coil generator would produce a waveform of Figure 22(b). The more coils added to the generator, the smoother the dc output voltage. Recall, also, that the added coils require the generator commutator to be divided into more segments.



(a) Two coil armature

(b) Three coil armature

Figure 22(a) - Generator output voltage (solid line) for a two coil armature. (b) - Generator output for a three coil armature.

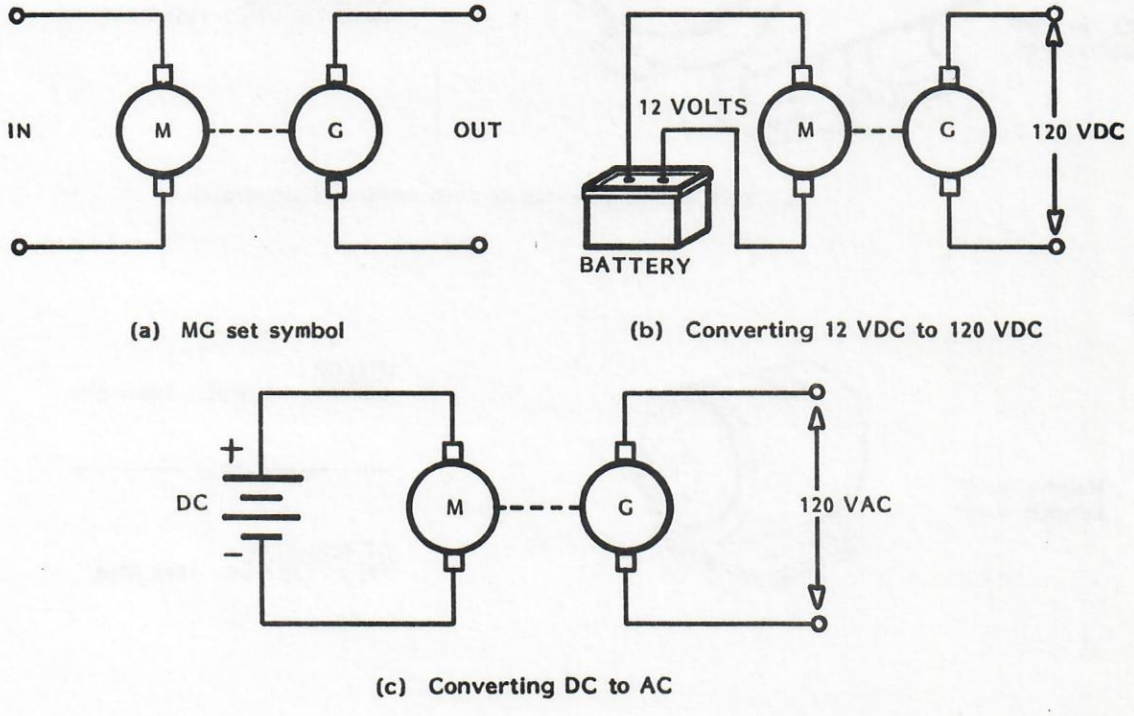
As shown in Figure 22(a) and (b), before the voltage from one coil drops down to zero volts, the voltage of the next coil appears at the output (45 degrees later in a) and brings the output up to maximum again. In Figure 22(b), with a three coil armature, the voltage starts to rise again after only 22.5 degrees. As shown by the solid line, the voltage variations, called RIPPLE, are reduced as the number of armature windings are increased.

GENERATOR LOADING

When a load is placed across the output voltage of the generator, current is drawn that must flow through the armature windings. This load current creates a new magnetic field across the armature that "opposes" the fixed magnetic field (according to Lenz's Law) and makes the armature of the generator more difficult to drive. Thus, as the current load on the generator output is increased, the prime mover has to work harder and apply more input torque and horsepower to maintain the generator speed and output voltage.

MOTOR-GENERATOR SET

A popular system used to generate voltage is the MOTOR-GENERATOR set, abbreviated as MG set. It consists of a motor coupled to a generator so that we have electrical power IN and electrical power OUT. This arrangement has the advantage of changing or converting the input voltage to another value or form. The MG set symbol and two applications are shown in Figure 23.



(a) MG set symbol

(b) Converting 12 VDC to 120 VDC

(c) Converting DC to AC

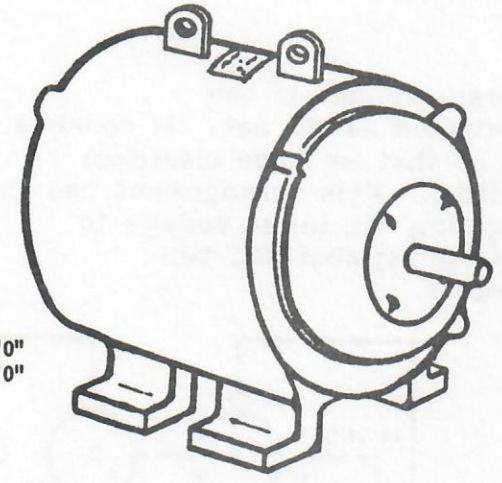
Figure 23(a) - Motor generator set symbol. (b) - MG set used for dc to dc conversion. (c) - MG set used for dc to ac conversion.

Using the MG set, typically, we could convert a low dc voltage to a high dc voltage as shown above in Figure 23(b). We could also convert dc to an alternating voltage output using an ac generator (also called an alternator) which is discussed later in AC.

RECIPROCITY

The word "reciprocity" means the "exchange of action." We are using the word here to mean that the same "rotating machine" can be used as a motor or generator. The word is also applied to radio antennas which can be used for either reception or transmission, a reciprocal action.

Consider the two machines shown in Figure 24 below, together with their specifictions. Both machines can be used as motors or as generators with the specifictions shown.



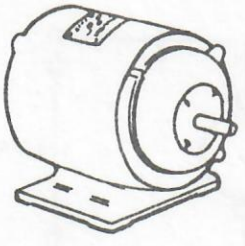
Height = 1'0"
Length = 2'0"

MOTOR
3 HP, 125 VDC, 1750 RPM

——— OR ———

GENERATOR
2kw, 125 VDC, 1750 RPM

(a) 3 HP rotating device as both motor and generator.



Height = 8"
Length = 9"

MOTOR
1/3 HP, 120 VDC, 1800 RPM

——— OR ———

GENERATOR
120W, 120 VDC, 1800 RPM

(b) 1/3 HP rotating device as both motor and generator.

Figure 24 - Motors used as generators illustrate the reciprocal concept.

CONCLUSIONS

We have learned from this information sheet that:

The purpose of a motor is to convert electrical energy into rotational mechanical energy.

The symbol for the motor is

An armature winding acts as an electromagnet and is repelled and attracted by the fixed magnetic field to create 180 degrees of rotation.

Reversing the polarity of the voltage applied to the armature causes another 180 degrees of rotation.

The polarity of the voltage applied to the armature is reversed at the correct time by the commutator and brush assembly.

To produce a more constant torque the number of armature windings are increased.

Increased armature windings require a greater number of segments on the commutator.

Torque is a function of the

number of conductors in the armature winding
length of the armature conductor
armature radius
armature current flow
field strength of the magnets

An increase in any of the above quantities increases the motor torque.

A rotating armature in the motor or generator generates a counter electromotive force abbreviated as a cemf.

The motor current drain is a function of the dc resistance of its armature and the cemf developed when rotating.

A running motor draws less current than the same motor running slowly or stalled.

As a motor is loaded, it slows down and draws more current.

Motor speed is measured in the number of revolutions per minute (rpm) of the armature shaft.

The amount of power a motor can deliver is indicated by its horsepower rating.

The efficiency of a motor is based on the amount of power consumed from the power source and the amount of power delivered to the load. It is calculated from

$$\% \text{ Eff} = \frac{P_{OUT}}{P_{IN}} \times 100$$

The purpose of a generator is to convert rotational energy into electrical energy.

The symbol for a generator is

The generator output voltage is a function of the

speed of rotation
strength of the fixed magnetic field
number of turns in the armature windings

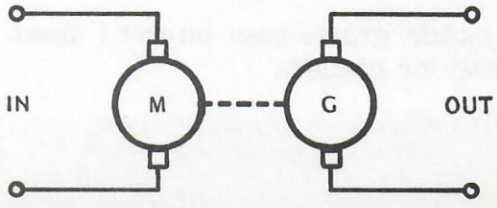
To get a purer, smoother output dc with less ripple, the number of armature windings must be increased.

When more current is drained from the generator a stronger cemf is generated in the armature.

When the cemf in the generator armature is increased it becomes harder to turn and thus places a greater load on the prime mover.

Motors and generators are coupled together creating motor-generator sets.

The symbol for an MG set is



ASSIGNMENT

Answer the following True-False questions.

1. An electric motor is used to produce electrical energy. _____

2. The operation of a motor depends upon the interaction of two magnetic fields. _____

3. When an armature is placed in a magnetic field the like poles repelling and unlike poles attracting will produce two 180 degree rotations for a total of 360 degrees. _____

4. The second 180 degree rotation of the armature must be accomplished by reversing the polarity of the applied potential to the armature. _____

5. The polarity of the voltage applied to the armature is reversed by the brush and commutator assembly. _____

6. The direction of rotation of a dc permanent magnet type motor can only be reversed by switching the power input polarity. _____

7. The rotational force developed by the motor armature is called Torque and is measured in foot-pounds. _____

8. Increasing the number of armature windings smooths out the delivery of torque by the armature. _____

9. If the number of armature windings is 8, then 16 segments are needed on the commutator. _____

10. An increase in the current flow in the armature will reduce torque. _____

11. The voltage induced in the motor armature is called the counter emf. _____

12. The current drawn by a motor is a function of the counter emf, the applied voltage and the dc resistance of the armature. _____

13. The greater the motor speed the greater the cemf and the less the current drained from the power source. _____

14. As the load on a motor armature increases, the motor rpm increases. _____

15. The speed of a dc motor is proportional to the applied voltage. ____

16. The horsepower that is delivered by a motor increases as the rpm increases. ____

17. Motor efficiency is equal to P_{IN}/P_{OUT} (100). ____

18. A generator is used to generate mechanical energy. ____

19. The output polarity of a generator using a permanent magnet field, can be reversed only by reversing the direction of rotation. ____

20. As the load on a generator is increased the cemf increases placing a greater load on the prime mover. ____

KEY TERMS

1. ARMATURE

   The moving part in an electromechanical assembly. In a motor or generator the coils that form the armature are wound on the "armature" shaft that rotates or is rotated.

2. BRUSH

   A device made of carbon or some other conductive material which is used to make connection to a rotating armature commutator in a motor or generator.

3. COMMUTATOR

   The part of the armature to which the coils of the motor or generator armature windings are connected. It consists of copper segments mounted in a circular form on the armature shaft. Connection is made to the commutator using brushes.

4. COUNTER EMF

   A voltage developed in a coil that opposes the applied voltage.

5. EFFICIENCY

   A motor rating equal to the ratio of power output to the power input.

6. GENERATOR

   A device that converts rotational energy into electrical energy.

7. HORSEPOWER

   A rating used to indicate how much mechanical power a motor can deliver.

8. MOTOR

   A device that converts electrical energy into rotational mechanical energy.

9. RECIPROCITY

   A mutual exchange. In the case of a dc motor or generator, it means that both can perform as either a motor or a generator.

10. RIPPLE

Variations in voltage amplitude of a dc generator. It is a function of the number of windings in the armature; the more windings the less the ripple.

11. TORQUE

A twisting or rotating force that causes rotation about an axis.

DC Motor Operation 7

OBJECTIVES

When you finish this experiment, you will be able to:

1. Wire and test a dc motor speed control circuit.
2. Calculate the armature resistance of a dc motor.
3. Calculate the counter emf developed by a rotating armature.
4. Wire and test a motor direction reversing circuit.
5. Calculate the input power to the motor under test.
6. Determine the horsepower output of the motor under test.

ADDITIONAL EQUIPMENT

a. Motor-Tach Assembly Card, CES 309.

b. 2 Banana to alligator clip adaptors (needed only if the CES 309 card is not used).

c. Digital or Analog Multimeter.

DESCRIPTION

The magnetic fields for direct current motors are created by permanent magnets called "field magnets" or by electromagnets called "field windings." There are many types of dc motors such as the small instrument motors used in tape recorders. These small motors have torques of 2.0 oz-in (ounce-inches). There are also medium and large size motors used to lift heavy loads.

The motor characteristics of interest are the ratings of Voltage, Current, Speed and Load capability which is rated in Torque or Horsepower, Size, Weight and cost. Also, most important is the motor's "Load Performance" which measures the decrease in speed versus load and the increase in current drain versus load.

In this experiment we will use very low power motors, as a convenience, to demonstrate the concepts and principles

involved. The characteristics and behavior of large motors will be different and the safety practices will also be different but the concepts tested here apply to the larger motors as well.

CES 309 MOTOR-TACHOMETER MODULE

The CES 309 module is of the plug-in type designed for use with the Ed-Lab 651 trainer. It consists of two identical PM (permanent magnet) dc motors whose shafts are coupled as indicated in Figure 1.

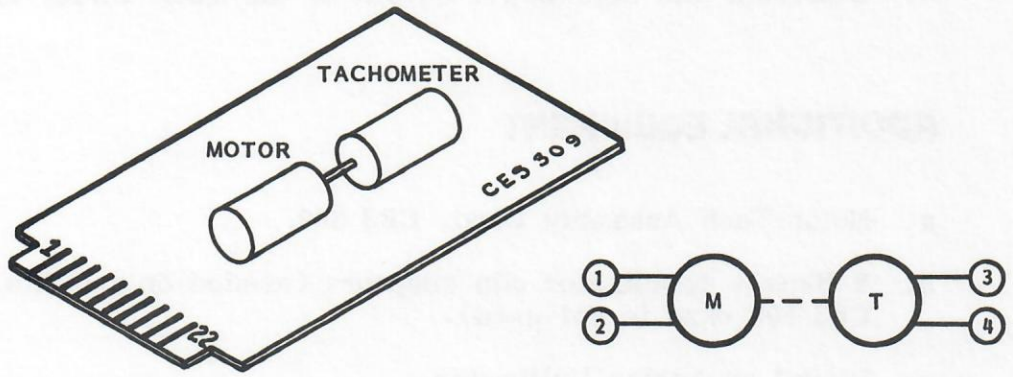


Figure 1 - The CES 309 Motor-Tach Module and its circuit and connector terminal numbers.

The word TACH is short for TACHOMETER which is a device used to measure rotational speed and, in this case, is a dc generator. The dc motor and generator used here are identical highly efficient, precision instrumentation motors.

In this experiment you will use the CES 309 module or you may use a single, unmounted, PM motor. The small precision PM motors generally rotate at 10,000 rpm. The motors used on the CES 309 module have an internal gearing system that reduces the shaft speed by a ratio of 50 to 1. This results in an output speed of 200 rpm.

The procedure of this experiment covers the following:

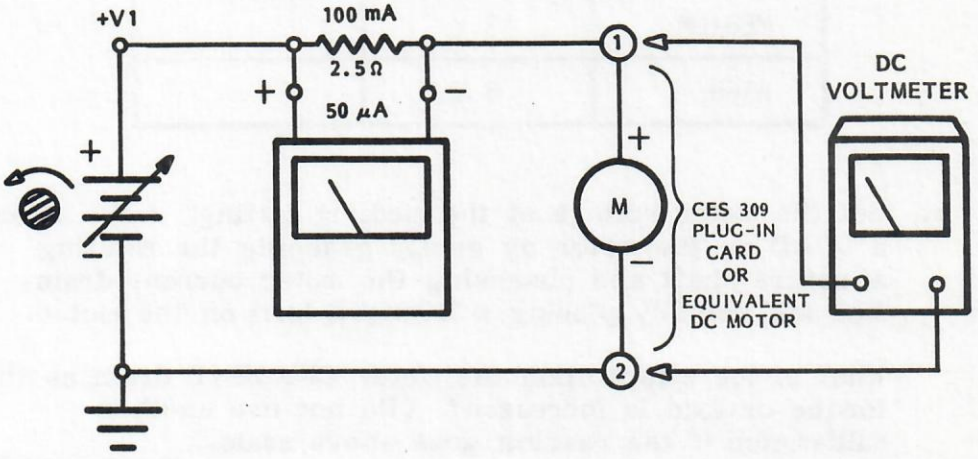
a. Motor Speed Control
b. Armature Resistance
c. Counter EMF
d. Motor Direction Control
e. Motor Power Rating Calculations
f. Motor Torque Calculations

PROCEDURE

1. Obtain the CES 309 Motor-Tach card or its equivalent. If a loose dc motor is used it must be compatible with the Ed-Lab trainer power source.

   Indicate the type of motor or module used.

2. Connect the dc motor to the +V1 voltage source as shown in Figure 2.



7.1 MOTOR SPEED CONTROL

3. Increase the +V1 voltage gradually from zero volts while observing the rotation of the motor shaft.

   At what voltage does the motor shaft start to turn?

   STARTING VOLTAGE = _____ VDC

   How does the value of the applied voltage affect the SPEED of the motor? _____

   _____

   _____

How does the value of the applied voltage affect the motor CURRENT drain? _____

_____

_____

4. Measure the current drain at three different speeds as listed below. Since you are reading current on the 100 mA range, read the 10 scale and multiply by 10.

SPEED	VOLTAGE	CURRENT
LOW	1 V	
MEDIUM	3 V	
HIGH	6 V	

5. Set the motor voltage at the medium setting, 3 V. Place a LOAD on the motor by gently grasping the rotating armature shaft and observing the motor current drain. You are actually placing a TORQUE load on the motor.

   What is the effect upon the motor CURRENT drain as this torque or load is increased? (Do not use another milliameter if the reading goes above scale.) _____

   _____

   _____

   _____

6. What is the effect on the motor SPEED when the torque or load is increased? _____

   _____

   _____

   _____

7.2 ARMATURE RESISTANCE

7. In order to determine the motor armature resistance, you can measure the current flow and the applied voltage with the motor stalled, that is, not running. When stalled, there is no electromagnetically induced counter

emf in the armature windings and thus the current is controlled only by the armature resistance.

Set +V1 to zero volts.

Hold the motor shaft so that it will not turn and then increase +V1 until the current reads 100 mA (full scale).

Record, below, the voltage measured across the motor.

STALLED MOTOR VOLTAGE AT 100 mA CURRENT	V_M = _____ VOLTS

Now release the motor shaft but do not change the +V1 voltage setting.

8. Read and record below, the new motor current drain.

ROTATING MOTOR CURRENT DRAIN	I_M = _____ mA

The rotating current drain is lower than the stalled 100 mA current drain from step 7. Why? _____

_____

_____

_____

Decrease the +V1 setting to zero volts.

9. Calculate the motor armature resistance from the voltage in step 7 using Ohm's Law.

ARMATURE RESISTANCE $R_A = \frac{E}{I}$

$$= \frac{V_M}{I_M} = \frac{V_M}{100\ mA} = \frac{(\quad)}{100\ mA}$$

ARMATURE RESISTANCE	R_A = _____ Ω

7.3 COUNTER EMF (CEMF)

10. To calculate the CEMF generated by the running motor refer to the equivalent circuit shown below in Figure 3.

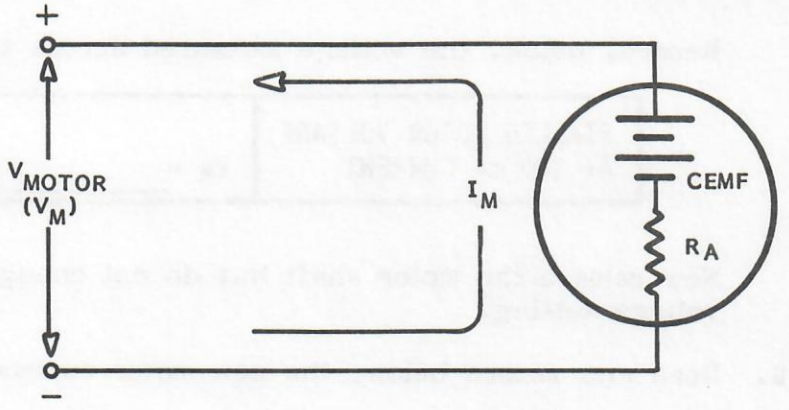


Figure 3 - Equivalent circuit of the motor, when running, shows the CEMF in series with the armature.

The reduced current drain when the motor armature is spinning is the result of the CEMF. The equation to determine the value of the CEMF is:

$$CEMF = V_M - (I_M R_A)$$

Substitute V_M from step 7
I_M from step 8
R_A from step 9.

CEMF = ( ) - ( )( )

( ) - ( )

CEMF = _____ VOLTS

This value of CEMF is valid only for the voltage applied in step 8 and the resultant motor speed.

11. Rotate the +V1 control knob to increase the driving voltage to 6 volts as read on the external voltmeter.

    Read the new no-load motor current, I_M.

    I_M = _____ mA

12. Calculate the new CEMF developed with a 6 volt input.

    CEMF = (6) - (I_M R_A)

    (6) - ( )( )

    (6) - ( )

    CEMF = _____ VOLTS

7.4 MOTOR DIRECTION

13. Reduce the +V1 voltage control to zero volts. Increase the voltage gradually until the motor just begins to rotate slowly.

    Is the rotation clockwise or counterclockwise? _____

14. Reverse the polarity of the voltage applied to the motor by switching the banana plugs between the +V1 and ground jacks.

    What happens to the motor rotation? _____

    _____

    What happens to the reading on the current meter? _____

    _____

    _____

7.5 MOTOR REVERSAL CIRCUIT

15. Remove the previous wiring and wire the Motor Direction Control circuit shown in Figure 4.

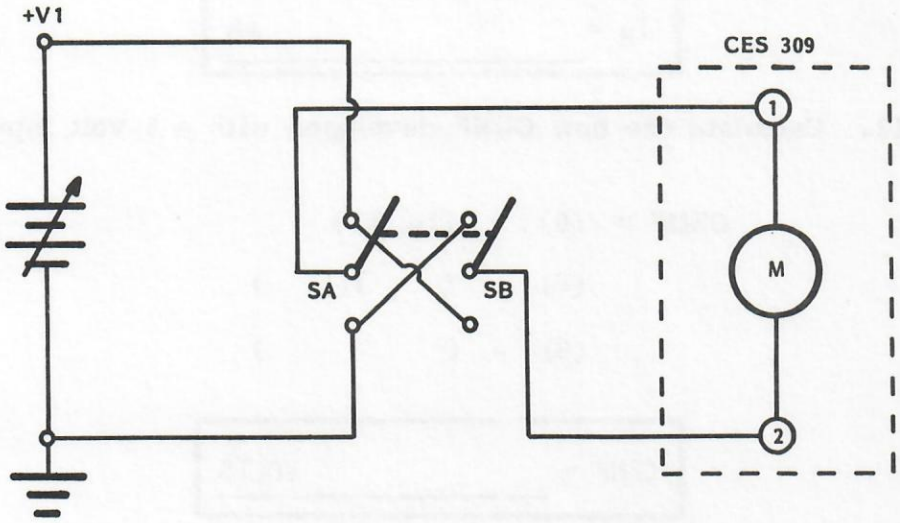


Figure 4 - Motor direction control circuit; EXPERIMENT.

16. Place both SA and SB in the UP position and observe the direction of rotation. (Reduce the motor speed (+V1) to make it easier to see the direction of shaft rotation.)

    What is the motor direction? _____

17. With the motor rotating, move both SA and SB DOWN at the same time. The dashed line between SA and SB in Figure 4 indicates that both switches should be moved together.

    What happens to the motor operation? _____

    _____

    _____

7.6 MOTOR POWER RATING

18. Calculate the motor input power based on the current drain I_M from step 11, and the applied voltage, 6 V.

$$\text{INPUT POWER}_M = (E)(I)$$

$$= (6)(I_M)$$

$$= (6)(\quad)$$

INPUT POWER $_M$ = _____ WATTS

19. Assuming a motor efficiency of 80% (a factor of 0.8), calculate the motor output power as follows:

$$P_{OUT} = (P_{in})(\text{Efficiency Factor})$$

$$= (\quad)(0.8)$$

P_{OUT} = _____ WATTS

20. Determine the horsepower rating of the motor given that 1 hp = 746 watts.

$$hp = \frac{P_{OUT}}{746}$$

$$= \frac{(\quad)}{746}$$

hp = _____ hp

21. Calculate the output torque in inch-ounces (in-oz) assuming a speed of 200 rpm. This can be accomplished by transposing the formula for hp given earlier in Information Sheet 4.

$$hp = (0.00019)(rpm)(Torque)$$

$$Torque = \frac{hp}{(0.00019)(rpm)} \qquad \text{(Use hp from step 20)}$$

$$= \frac{(\qquad)}{(0.00019)(200)}$$

Torque = _____ ft-lbs

To convert the torque in ft-lbs to torque in ounce-inches, multiply as follows:

Multiply the torque in ft-lbs by 12 inches and 16 oz as shown below and cancel ft and lbs.

$$(\text{Torque ft-lbs}) \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{16 \text{ oz}}{1 \text{ lb}}$$

We can now multiply the torque in foot pounds by 12 x 16 to result in the torque in oz-in. Thus:

Torque in oz-in = Torque in ft-lbs (12)(16)

= ( )(192)

Torque = _____ oz-in

7.7 MOTOR PROJECT (OPTIONAL)

If a motor kit is available, you may wish to assemble one to demonstrate motor and generator action. The motor kits require an external power source (batteries) as the motors draw a high current.

The kits are available in two pole (two windings) or three pole (three windings) types of armatures. The three pole

types are self-starting while the two pole armature must be spun to start. A typical motor constructed from a kit is shown in Figure 5.

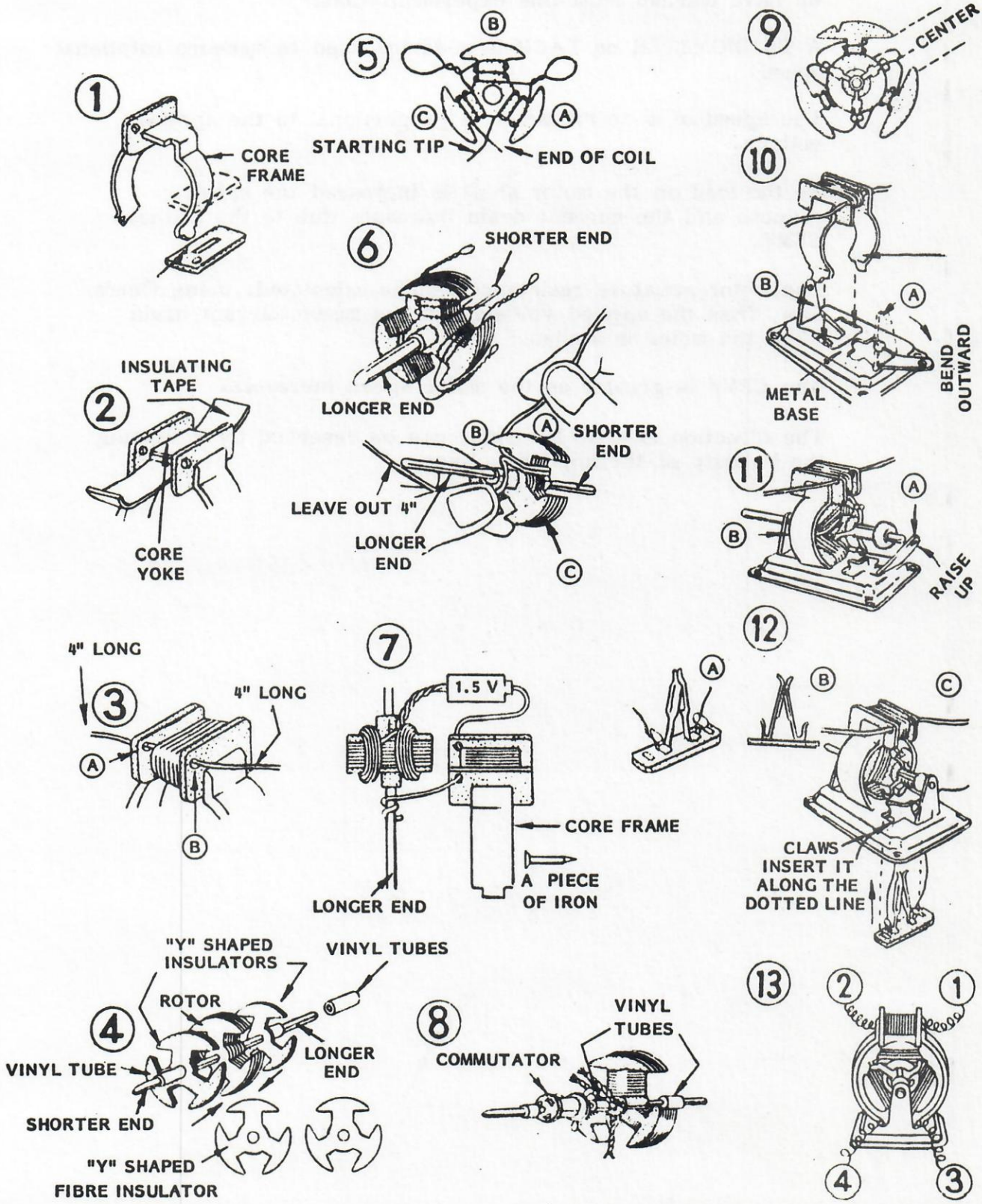


Figure 5 - Assembly instructions for a dc motor with an electromagnetic field winding and a 3 pole armature. Courtesy of IAS Company.

CONCLUSIONS

We have learned from this experiment that:

A TACHOMETER or TACH is a device used to measure rotational speed.

The speed of a dc PM motor is proportional to the applied voltage.

As the load on the motor shaft is increased the speed reduces and the current drain increases due to the reduced CEMF.

The motor armature resistance can be calculated, using Ohm's Law, from the applied voltage and the motor current drain when the motor is stalled.

The CEMF is greater as the motor speed increases.

The direction of a dc PM motor can be reserved by reversing the polarity of the applied voltage.

ASSIGNMENT

Answer the following True-False questions.

1. A tachometer, used to measure rpm, is basically a dc generator. _____

2. As the tachometer voltage output increases, it indicates a reduced speed. _____

3. The speed of a dc motor is proportional to the applied voltage. _____

4. If a dc PM motor is rated at 6,000 rpm at 6 volts, at 0.2 volts it will rotate at 200 rpm. _____

5. If the voltage applied to a dc motor is doubled its current drain also doubles. _____

6. As the load on a motor is increased its current drain increases. _____

7. Motor speed decreases as the load is increased but the CEMF increases to compensate for the speed drop. _____

8. Armature resistance increases with speed and applied voltage. _____

9. The CEMF generated by the armature is directly proportional to the armature rotational speed. _____

10. In a dc PM motor, direction of rotation is determined by the polarity of the applied voltage. _____

Solve the following problems.

11. Draw the circuit of a motor and a dpdt direction reversal switch.

12. Draw the circuit of a PM dc motor wired to a 4 level resistive starter.

13. Calculate the armature resistance of a stalled motor connected across a 120 volt power line that draws a current of 2A.

14. A dc PM motor has an armature resistance of 30 ohms. When connected across a 120 volt source, the running motor draws a current of 1.5 A. Calculate the CEMF generated by the armature.

KEY TERMS

1. ARMATURE

   The moving part of the motor; the rotor or motor shaft.

2. ARMATURE RESISTANCE

   The dc resistance of the wire used to wind the armature on the motor shaft.

3. FIELD WINDING

   The electromagnet winding that surrounds the motor armature winding.

4. HORSEPOWER

   A rating used to indicate how much mechanical power a motor can deliver.

5. TACHOMETER

   A device used to measure rotational speed. The tachometer may be designed to operate mechanically, electrically or optically.

Generators and Motor Generator Sets

8

OBJECTIVES

When you finish this experiment, you will be able to:

1. Describe the construction of a dynamotor and list its advantages.
2. Draw the symbol of an LED and show it wired in the forward and reverse configurations.
3. Energize an LED from the generator output to show output polarity.
4. Demonstrate generator loading due to opposing magnetic fields.
5. Compare motor current drain to the generator load.
6. Calculate power input and output and motor-generator efficiency.
7. Use the generator as a calibrated tachometer.
8. Test, plot and calculate the generator speed regulation characteristics.
9. Manually regulate the motor speed for a constant generator output voltage.

ADDITIONAL EQUIPMENT

a. Motor-Tach Assembly Card, CES 309

b. Digital Multimeter

DESCRIPTION

It is often necessary to convert from one form of electricity to another. One method of converting is to couple a motor and generator together as on the CES 309 module card. The motor and generator may be either ac or dc types. The most often used combinations are:

Dc in dc out - Step up without the use of transformers which cannot operate on dc.

Dc in ac out - Conversion of dc battery supply to ac for use with appliances.

GENERATOR

The same dc machine used as a motor can also act in the opposite manner as a generator to convert rotational energy into electrical energy.

DYNAMOTORS

While the motor-generator set is made up of separate units it is possible to construct the combination on a common armature shaft and a common set of field coils as shown in Figure 1. This type of construction is called a DYNAMOTOR and is much more efficient than the separate motor-generator (M-G) combination. The major improvement comes from the elimination of the flexible coupling no longer needed due to the common armature shaft.

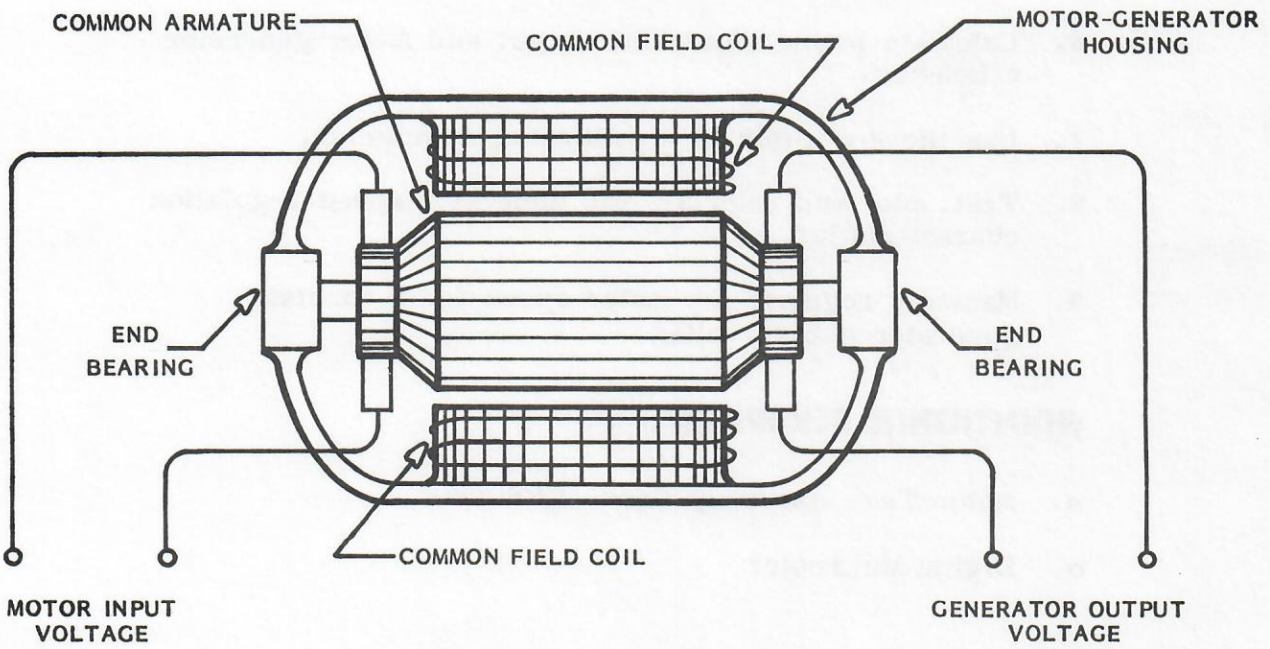
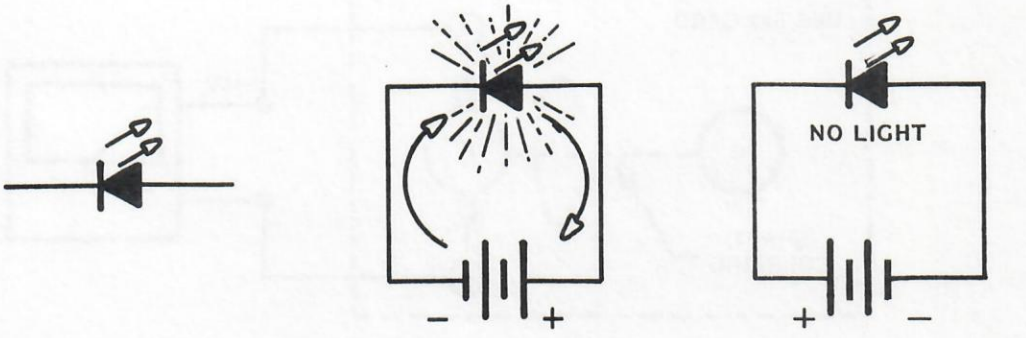


Figure 1 - Motor-generator assembly using a common shaft is called a Dynamotor.

The use of the dynamotor increases the efficiency and reduces the physical size as compared to a separate motor-generator combination. As shown in Figure 1, the motor commutator is on one end and the generator commutator on the other end of the shaft. The separate armatures are wound in the same slots. The efficiency of the dynamotor is between 50% to 60%. The efficiency of a motor-generator set is much less.

LIGHT EMITTING DIODES

A LIGHT EMITTING DIODE, known as an LED, is a diode that emits light (usually red or green) only when current flows through it in the forward direction. The symbol for an LED is shown in Figure 2(a) where it is shown to be the same as an ordinary diode but with the addition of the arrows to indicate light emission.



(a) LED SYMBOL (b) FORWARD BIASED LED (c) REVERSE BIASED LED

Figure 2 - LED symbol and forward and reverse biased states.

In the procedure of this experiment you will observe that the voltage output of a dc generator appears with the slightest rotation of the generator shaft. You will be able to energize an LED and observe the uni-directional current characteristics of the LED. The LED is used in this experiment because it is a low power load than can be visually observed. The generator loading characteristics are then tested to prove the concept of opposing magnetic fields explained earlier in Information Sheet 4.

The complete M-G set is then wired and the motor current drain versus speed and generator load is tested. You will then perform various calculations related to voltage losses and efficiency of the M-G set.

The M-G set then uses the generator as a calibrated "tachometer" to measure rotational speed and, finally, the generator output regulation is tested and calculated.

PROCEDURE

1. Plug the CES 309 Motor-Tach (or generator) module card into the PC socket making sure that pin 1 is on the upper left side.

8.1 GENERATOR OUTPUT

2. You will use the same dc rotating machine used in the previous experiment as a motor but you will now use it as a generator.

   Wire the circuit shown in Figure 3.

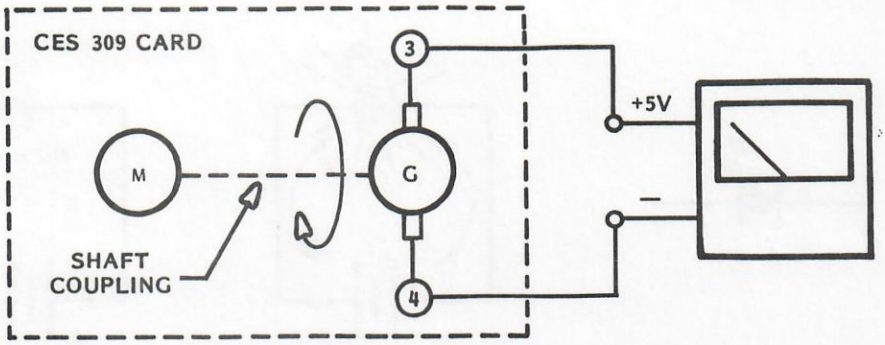


Figure 3 - Generator output voltage EXPERIMENT.

3. Grasp the shaft coupling between your fingers and spin the generator shaft CW.

   What does the meter indicate? _____

   _____

   _____

   Spin the generator shaft in the opposite direction, CCW. What does the meter indicate? _____

   _____

8.2 LED LOAD

4. Disconnect the meter and connect the LED across the generator output as shown in Figure 4.

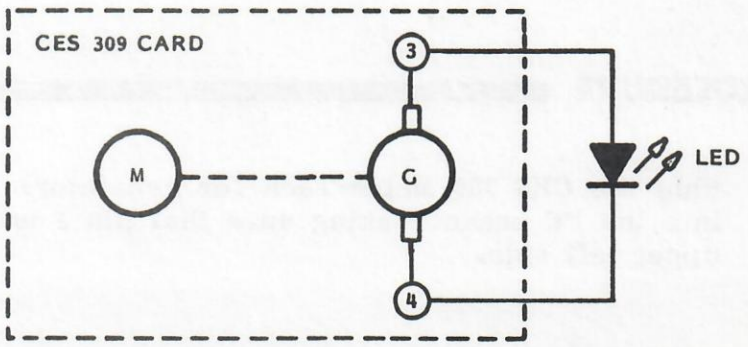


Figure 4 - LED load across generator output; EXPERIMENT.

5. Rotate the generator shaft, first in one direction and then in the other direction.

   Does the lamp light in one or both directions of rotation?

   _____

   Why doesn't the lamp light when the generator is rotated CCW?

   _____

   _____

   _____

   _____

   If the lamp is lit in one direction of the rotation can you conclude that you have generated an electrical current flow?

   _____

8.3 GENERATOR LOADING

6. It was indicated in Information Sheet 4, DC Motors and Generators, that when a generator is "loaded" the current flow creates an opposing magnetic field resulting in a force that makes it more difficult to turn the generator shaft. This effect is illustrated below.

   Wire the new circuit shown in Figure 5.

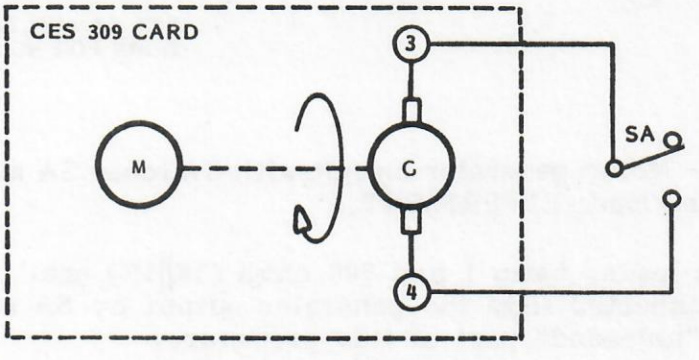


Figure 5 - Circuit used to illustrate generator loading; EXPERIMENT.

7. Place Switch SA in the UP position for the no-load condition.

   Spin the generator shaft and note the ease with which the shaft turns.

8. Now place Switch SA DOWN for the "generator loaded" condition.

   Spin the generator shaft and note the effort required. How would you compare the force needed to turn the generator shaft in steps 7 and 8?

8.4 UNLOADED MOTOR-GENERATOR (MG) OPERATION

9. Turn +V1 down to zero volts output.

10. Wire M-G combination as shown in Figure 6.

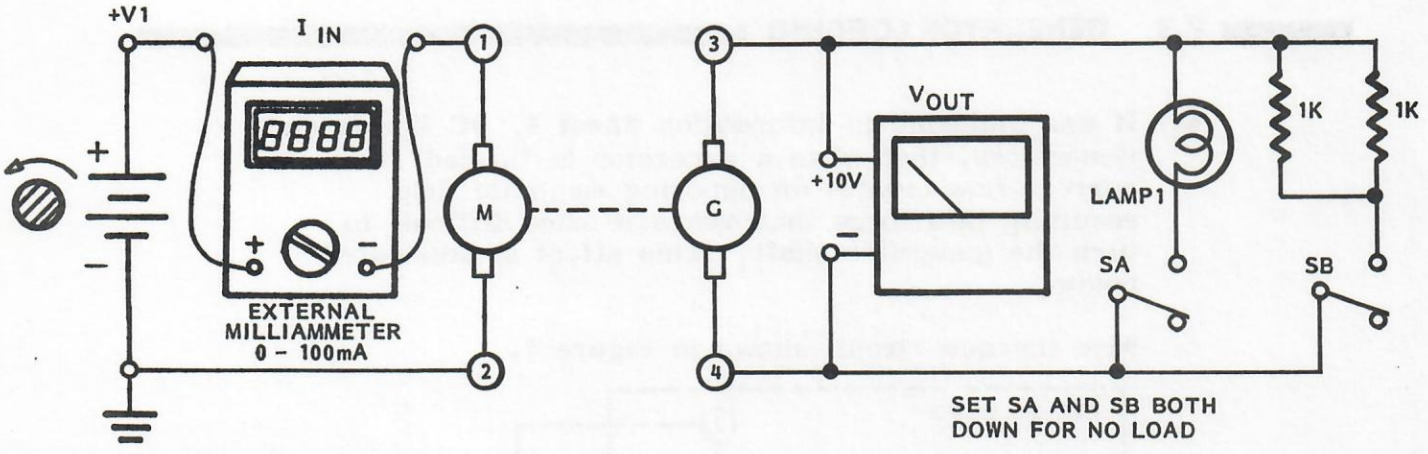


Figure 6 - Motor-generator circuit with Switches SA and SB open for no load; EXPERIMENT.

Both loads, Lamp 1 and 500 ohms (1K||1K) are disconnected from the generator output by SA and SB for the "unloaded" part of this procedure.

11. Slowly increase the +V1 voltage to 6 volts and observe the input current and the output voltage.

    What occurs with the input current?

What occurs with the generator output voltage?

What happens to the motor speed as +V1 is increased?

8.5 LOADED MG OPERATION

12. Set +V1 to maximum, 9 volts.

13. Switches SA and SB should still be in the DOWN position for no load.

Read the NO LOAD input current ($I_{IN\ NL}$) and output voltage ($V_{OUT\ NL}$) and enter the readings in Table 1 on line (a), NO LOAD.

LOAD		SWITCHES	I_{IN}	V_{OUT}
a.	NO LOAD	A & B DOWN		
b.	500 Ω LOAD ONLY	A DOWN, B UP		
c.	LAMP ONLY	A UP, B DOWN		
d.	500 Ω PLUS LAMP	A & B UP		

TABLE 1 - Motor input current versus generator load and output voltage.

14. Repeat the measurements for the three loaded conditions as shown in lines b, c and d of Table 1 and enter the data.

15. Analysis of the data in Table 1 shows that:

As the load current is increased, the input current _____ (increases/decreases).

As the load current is increased, the output voltage _____ (increases/decreases).

8.6 POWER AND EFFICIENCY

16. Calculate the input power for the 500 ohm load (line b) only.

$$P_{IN\ (b)} = V_{IN}\ I_{IN}$$

$$= (9V)(\quad)$$

$P_{IN\ (b)}$ = _____ mW

17. Calculate the generator output power.

$$P_{OUT\ (b)} = \frac{V_{OUT}^2}{R}$$

$$= \frac{(\quad)^2}{500} = \frac{\quad}{500}$$

P_{OUT} = _____ mW

18. Calculate the efficiency of the M-G system. (It will be very low.)

$$\%\ Eff = \frac{P_{OUT}}{P_{IN}} x\ 100$$

$$= \frac{(\quad)}{(\quad)}\ x\ 100$$

Eff = _____ %

The efficiency of a standard motor-generator set is much higher than that of the CES 309 MG set because the construction is different.

19. It is possible to calculate the Voltage and Power Loss in the generator internal resistance (armature resistance). With a 500 ohm load, the output current is

$$I_{OUT} = \frac{V_{OUT}}{R_{LOAD}} = \frac{(\quad)}{(500)}$$

Enter V_{out} from Table 1, step 13, line (b.)

I_{OUT} = _____ Amps

20. The armature resistance was calculated to be 19 ohms earlier in Experiment 7 and can now be used to determine the power (I^2R) loss.

$$P_{LOSS} = I^2 R_{ARM}$$

$$= (I_{OUT})^2 (R_{ARM}) \qquad (I_{out} \text{ from step 19})$$

$$= (\quad)^2 (19)$$

GENERATOR ARMATURE COPPER LOSS	P_{LOSS} = _____ mW

21. The voltage loss in the internal resistance of the armature (19 ohms) is:

$$V = I_{OUT} \; R_{ARM}$$

$$= (\quad) (19)$$

V_{LOSS} = _____ VOLTS

The output voltage drop, V_{LOSS} from above which should be approximately 0.23 volts is due to copper losses in the armature winding. The major drop in output voltage resulted from the loss of motor speed when the load was applied.

8.7 MG SET APPLICATION

A motor-generator set is used on a small boat to convert 12 volts to 120 volts to allow the use of certain appliances. The circuit of Figure 7 shows the hook-up and typical measurements.

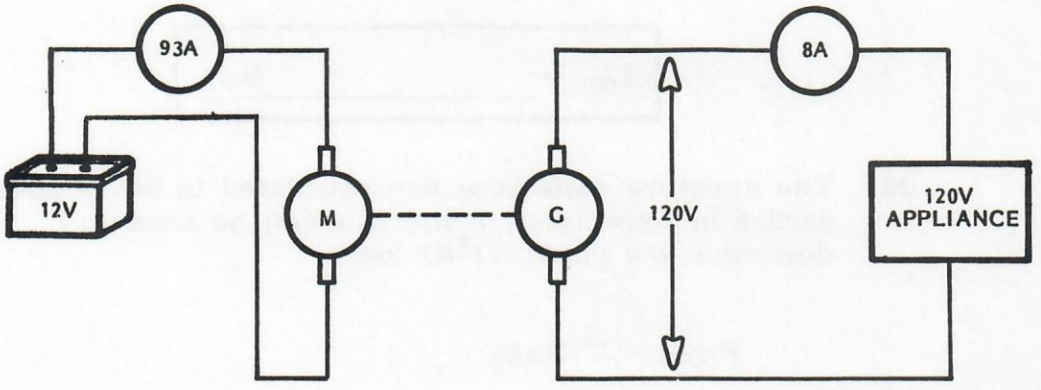


Figure 7 - Example of an M-G application that can be found on a small boat.

22. Calculate the following for the circuit of Figure 7.

(a) POWER IN

$$P_{IN} = E_{IN} \cdot I_{IN}$$

$$= (12)\ (93)$$

P_{IN} = _____ WATTS

(b) POWER OUT

$$P_{OUT} = E_{OUT} \quad I_{OUT}$$

$$= (120)\ (8)$$

P_{OUT} = _____ WATTS

(c) EFFICIENCY

$$\% \text{ EFFICIENCY} = \frac{P_{OUT}}{P_{IN}} \times 100$$

$$= \frac{(\quad)}{(\quad)} \times 100$$

EFFICIENCY = _____ %

8.8 TACHOMETER OR SPEED MEASUREMENT

23. The speed of rotation of the generator determines the output voltage under no-load conditions. If a voltmeter is connected to the generator output the meter can be calibrated to read in speed or rpm as well as voltage. When used in this manner, the generator-meter combination is called a TACHOMETER.

24. Remove the existing wiring and assemble the circuit shown in Figure 8.

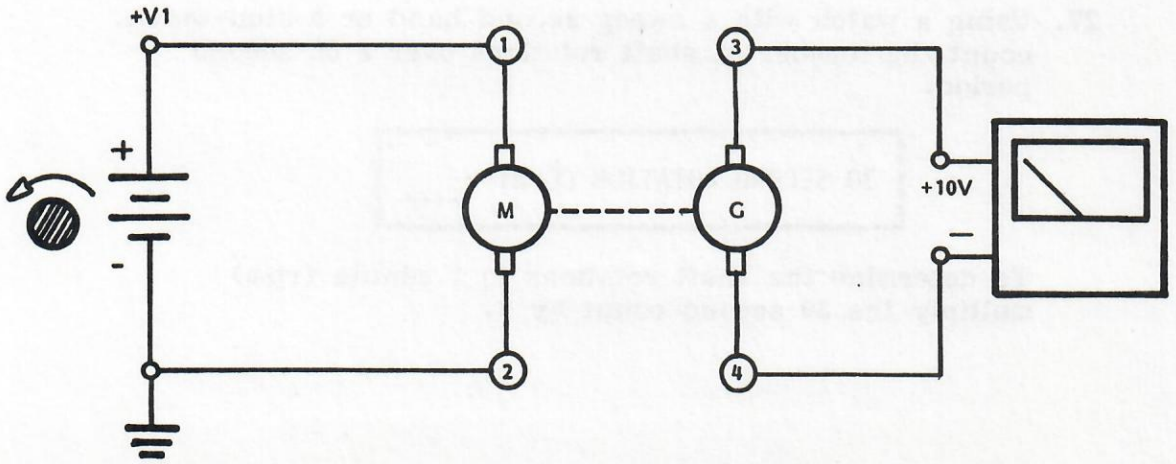


Figure 8 - Basic tachometer circuit; EXPERIMENT.

25. Vary the +V1 control from 0 volts to maximum (9 V) and observe the generator output voltage on the meter.

    Enter the output voltage readings for 4 arbitrary speed levels in Table 2.

SPEED	V_{OUT}
ZERO (+V1 = 0 V)	0 V
LOW	V
MEDIUM	V
HIGH (+V1 = 9 V)	V

TABLE 2 - Speed versus output voltage.

How does the output voltage change with the speed of rotation?

_____

_____

8.9 TACHOMETER CALIBRATION

26. Set the +V1 control to produce an output voltage of 1 or 2 volts as indicated on the panel meter, whichever voltage is most convenient to enable you to count the shaft coupler rotations.

SELECTED OUTPUT VOLTAGE ____ V

27. Using a watch with a sweep second hand or a stop-watch, count the number of shaft rotations over a 30 second period.

30 SECOND ROTATION COUNT = ____

To determine the shaft rotations in 1 minute (rpm) multiply the 30 second count by 2.

RPM = 30 second count x 2

= ( ) (2)

SHAFT ROTATIONS IN 1 MINUTE AT	RPM = _____
_____ $VOLTS_{OUT}$	

28. To obtain a Scale Factor, divide the rpm by the output voltage as shown below.

$$\text{SCALE FACTOR} = \frac{\text{RPM}}{V_{OUT}}$$

$$= \frac{(\quad)}{(\quad)}$$

SCALE FACTOR = _____ RPM/VOLT

29. We wish to run the motor at 200 rpm. What is the corresponding output voltage for 200 rpm?

$$V_{200\ RPM} = \frac{200\ \text{RPM}}{\text{SCALE FACTOR}} = \frac{200}{(\quad)}$$

$V_{200\ RPM}$ = _____ VOLTS

30. Adjust the +V1 control so that the motor generator runs at 200 rpm.

How did you adjust the speed to 200 rpm?

8.10 DIRECT METER SCALE RPM READINGS

31. It is possible to calibrate the meter that indicates the generator output voltage to read directly in rpm. This is done by placing a resistance in series with the meter and adjusting the resistance value so that the meter scale readings correspond to rpm. Recall that when a generator is used to measure speed, it is called a TACHOMETER.

Disconnect the lead from pin (3) of the generator that is connected to +10 V terminal of the meter and replace the lead with a 1 Meg pot as shown in Figure 9.

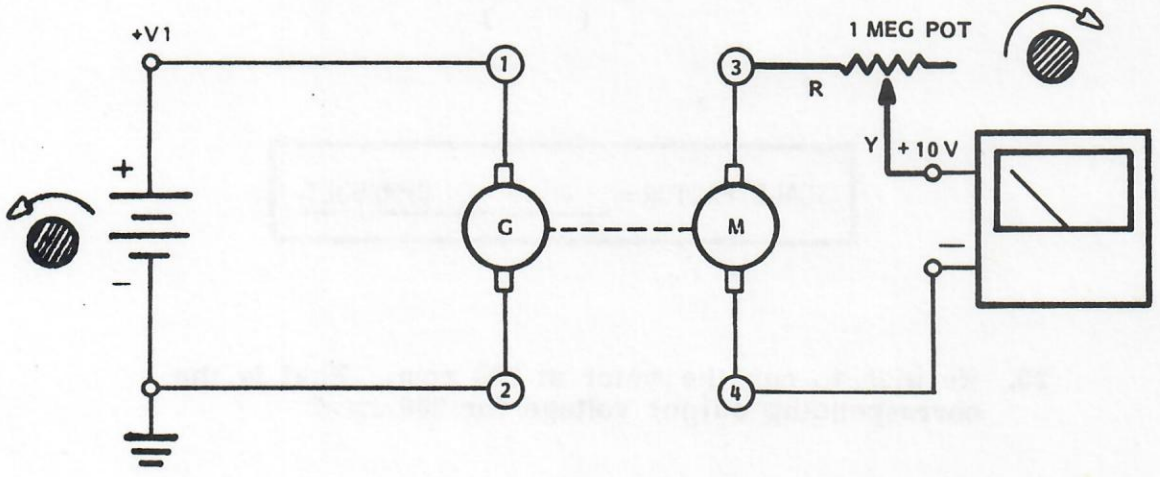


Figure 9 - Bold lines show the addition of the 1 Meg Calibration pot; EXPERIMENT.

32. The 0 to 50 scale calibration will be used to correspond to 0 to 500 rpm. To read rpm on this scale multiply any reading by 10.

Adjust the 1 meg pot fully clockwise so that the meter is reading directly on the 10 volt scale.

Adjust +V1 so that the meter reads the voltage calculated in step 29 that corresponds to 200 rpm.

FROM STEP 29

$V_{200\ RPM}$ = _____

33. Now rotate the 1 Meg pot counterclockwise until the meter reads 20 on the 50 scale which is the equivalent of 200 rpm (20 x 10).

    The calibration is now complete.

34. Vary the +V1 voltage control to result in different speeds as indicated in Table 3 below. The meter will now read in rpm directly on the 0 to 50 scale x10.

SPEED RPM	METER (0 TO 50 SCALE)
50	5
100	10
150	15
200	20
300	30
400	40
500	50

TABLE 3 - Speed versus meter readings.

8.11 GENERATOR PERFORMANCE CHARACTERISTICS

A generator provides a voltage to power some equipment. It is generally desired that this voltage output be constant despite any changes in load. The performance characteristic of the generator is the OUTPUT VOLTAGE TO LOAD CURRENT curve as shown in Figure 10 on the next page.

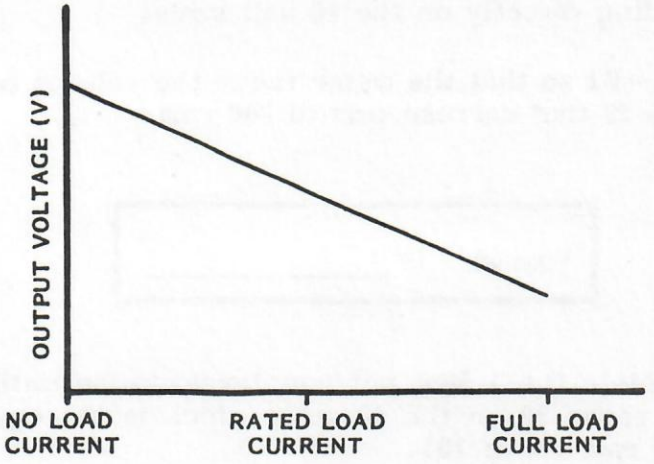


Figure 10 - Generator output voltage versus load current.

8.12 GENERATOR VOLTAGE REGULATION

35. Wire the circuit shown in Figure 11.

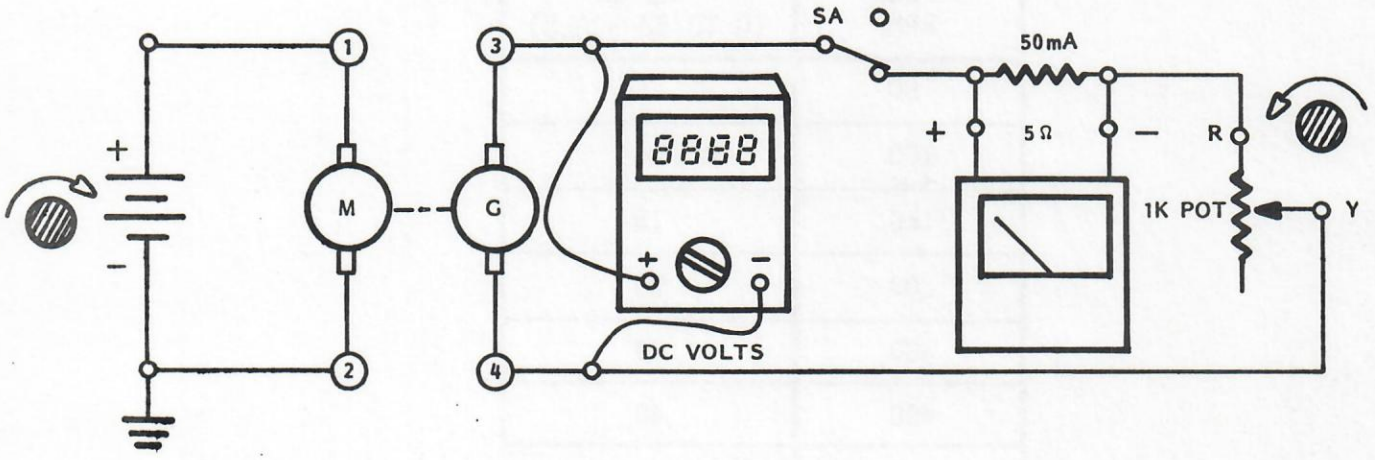


Figure 11 - Circuit to test Voltage vs Load characteristics; EXPERIMENT.

36. Set +V1 at maximum, +9V.

Set Switch SA DOWN (closed).

Set the 1K pot fully counterclockwise for maximum resistance.

37. Apply power and adjust the 1K pot for a full-load reading of 40 mA and record the output voltage on the corresponding line in Table 4.

LOAD CURRENT mA	OUTPUT VOLTAGE
40	
30	
20	
10	
0	

TABLE 4 - Output voltage versus load current.

38. Increase the 1K pot load resistance for each of the currents listed in Table 4 and enter the voltage readings.

    Open Switch SA (UP) for a no-load reading and enter the voltage in the Table.

39. Plot the generator VOLTAGE versus LOAD CURRENT curve on the graph in Figure 12.

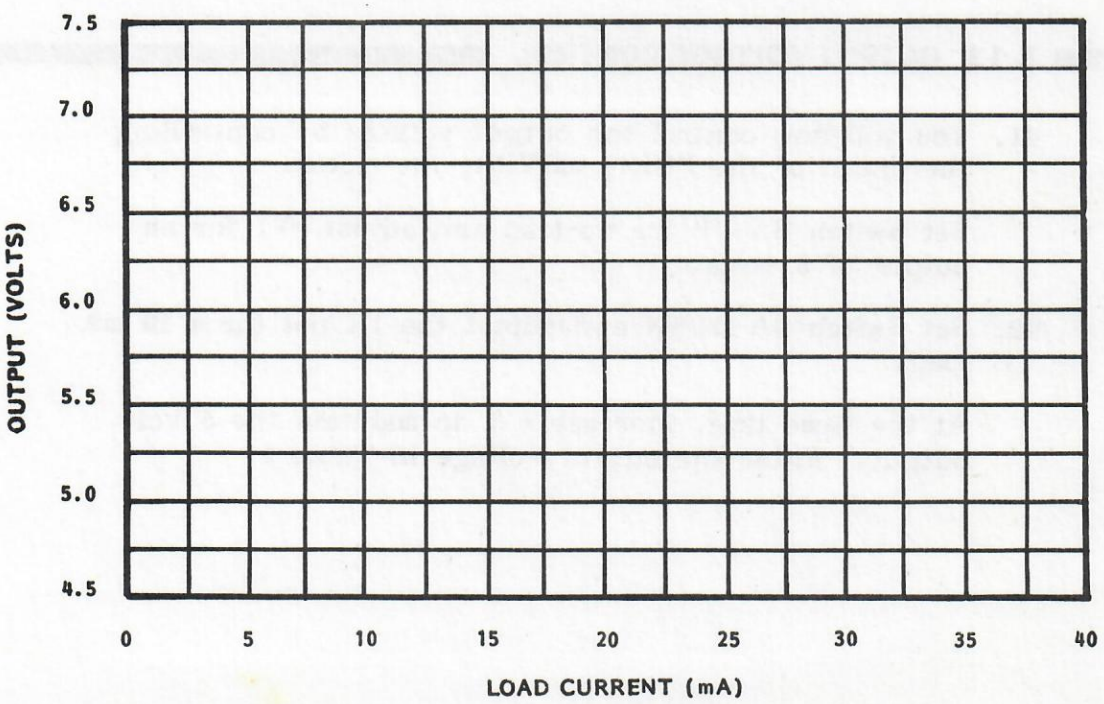


Figure 12 - Generator Output Voltage versus Load Current characteristics; EXPERIMENT.

Does the output voltage vary with the load? _____

40. Calculate the percentage of change in output voltage from no load to full load using the formula below.

$$\% \text{ change} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100$$

where E_{NL} = no-load voltage
E_{FL} = full-load voltage

$$= \frac{(\quad) - (\quad)}{(\quad)} (100)$$

VOLTAGE REGULATION	change = _____ %

The ability to maintain a constant output voltage with a varying load is called REGULATION. The motor generator set displays a regulation of approximately 34% (with 0% being perfect.)

Do you think this variation in output voltage would be acceptable if it were the 120 volts delivered to your home outlets?

_____

8.13 OUTPUT VOLTAGE CONTROL

41. You will now control the output voltage by controlling the speed of the PRIME MOVER, the motor.

    Set Switch SA UP for no-load and adjust +V1 for an output of 5 volts.

42. Set Switch SA DOWN and adjust the 1K pot for a 10 mA load.

    At the same time, increase +V1 to maintain the 5 volt output. Enter the output voltage in Table 5.

LOAD CURRENT mA	OUTPUT VOLTAGE	
0	5	E_{NL} (NO-LOAD)
10		
20		
30		
40		E_{FL} (FULL-LOAD)

TABLE 5 - Corrected output voltage versus load current; EXPERIMENT.

43. Adjust the 1K pot and +V1 to obtain each of the additional load currents listed in Table 5 and still maintain an output of 5 volts by adjusting +V1, the motor voltage (prime mover). List the voltage in Table 5 above. (It should remain at 5 volts.)

44. Plot the results of the voltage-load data listed in Table 5 on the graph of Figure 12.

How do the two curves compare? _____

_____

_____

Calculate the % Regulation for the data in Table 5 using the formula

$$\% \text{ REGULATION} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100$$

$$= \frac{(\quad) - (\quad)}{(\quad)} (100)$$

VOLTAGE REGULATION	% REGULATION = _____ %

We can conclude that it is possible to achieve constant output voltage over a range of varying load conditions by controlling the prime mover speed. While control was accomplished manually in this experiment, there are techniques that perform this automatically with feedback control circuits but are beyond the scope of this experiment.

CONCLUSIONS

We have learned from this experiment that:

A motor-generator built with a common armature shaft and field coils is called a DYNAMOTOR.

Certain types of diodes are built to emit light when forward biased and are called Light Emitting Diodes or LEDs.

The polarity of the dc generator output can be reversed by reversing the direction of rotation of the generator shaft.

The more the generator output is loaded the more difficult it is to turn the generator shaft.

The greater the load placed on the generator, the greater the load placed on the motor and the more current the motor draws from the power line.

A generator can be used as a tachometer to measure rotational speed.

The output voltage of the generator drops as the current load increases. This characteristic is called the generator Regulation.

The generator Regulation can be calculated from:

$$\% \text{ REGULATION} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100$$

The better the regulation characteristics of the generator the lower the % of regulation you will calculate.

ASSIGNMENT

Answer the following True-False questions.

1. A motor-generator system that is built on a common shaft with common field electromagnets is called a dynamometer. ____

2. An LED will light only when current flows through it in the forward direction. ____

3. The output polarity of a dc generator will reverse if the direction of shaft rotation is reversed. ____

4. As the current load on a generator is increased its shaft becomes easier to turn. ____

5. As the current load on the generator is increased the motor current drops an equal amount. ____

6. The efficiency of a separate motor and generator connected by a flexible coupling is typically lower than an equivalent dynamotor. ____

7. M-G sets and dynamotors are most likely to be used from dc to dc or dc to ac. ____

8. The voltage output of an unloaded generator can be calibrated to act as a tachometer. ____

9. If a generator output has a scale factor of 500 rpm to 1 volt then a 5 volt output is equivalent to 100 rpm. ____

10. The generator regulation characteristic can be calculated from ____

$$\% \text{ REGULATION} = \frac{E_{FL} - E_{NL}}{E_{FL}} \times 100$$

Perform the calculations listed below.

11. A generator has a no load output of 50 volts. When an 80 ohm resistor is connected across the generator the terminal voltage drops to 40 volts.

    a. Calculate the generator internal voltage drop.

    b. Calculate the current load on the generator.

    c. Calculate the internal resistance of the generator.

    d. Calculate the percentage of regulation for the generator.

KEY TERMS

1. DYNAMOTOR

   A rotary machine that changes a dc input voltage to a higher value. It is a motor and dc generator constructed on one shaft with common field coils.

2. LIGHT EMITTING DIODE (LED)

   A diode that emits light when it is forward biased.

3. REGULATION

   The ability of a power source to hold a constant voltage output when the load current is changed.

4. REGULATION % (VOLTAGE)

   The regulation characteristics of a voltage source is measured in percentage and calculated from

$$\% \text{ regulation} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100$$

   where NL = no load
   FL = full load

   The lower the percentage the better the regulation.

5. TACHOMETER GENERATOR

   A small dc generator connected to a voltmeter. The voltmeter is calibrated in rpm. The generator shaft is coupled to a device whose rotational speed is to be measured and the rpm is read from the meter scale.

Forces and Resistance

INFO SHEET 5

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Write the formulas that define the forces between electrical charges, magnetic charges and masses.
2. Explain why different materials have different resistances.
3. Define the effects of increasing diameter and length of a wire on its resistance.
4. Convert wire diameter into cross-sectional area.
5. Define and list the various Temperature Coefficients.
6. Define what is meant by the Specific Resistance of a material.
7. Use a Wire Gauge table to determine diameter, cross-sectional area and resistance per thousand foot length.
8. Convert from resistance to conductance or conductance to resistance.

DISCUSSION

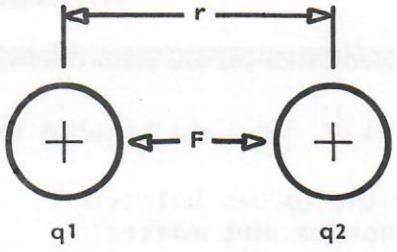
Previous experiments contained discussions on the forces created by unlike charges in static electricity and by unlike magnetic poles. There is also a force with which we are all familiar called GRAVITY, a force between two masses such as planets, or between a planet and its moons.

FORCES

The equations governing these forces are all similar and are given on the next page.

In Figure 1(a), the static charges are measured in coulombs, the distance in meters and the resulting force, F, is in newtons, N.

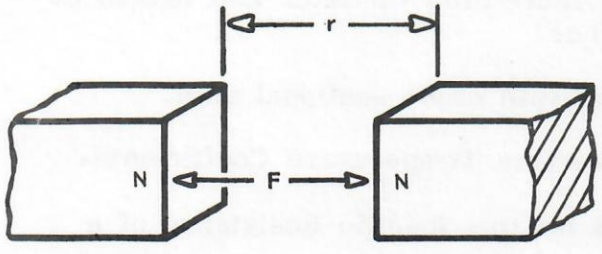
In Figure 1(b) the two magnets are suspended in a medium whose permeability, μ, is 1 (vacuum or air which is very close to 1). If the two magnetic fields, m1 and m2, are in MKS (SI) units for pole strength, AT/m, the resulting force, F, is in newtons, N.



$$\text{FORCE } (F) = K1 \frac{(q1)(q2)}{r^2} \quad (1)$$

q = CHARGES

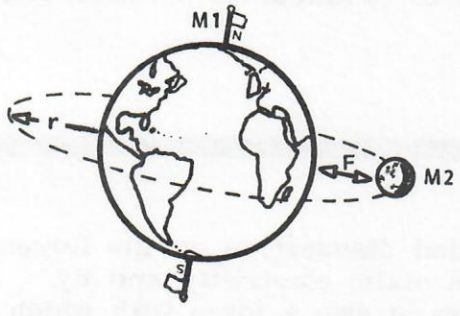
(a) STATIC ELECTRIC FORCES



$$\text{FORCE } (F) = K2 \frac{(m1)(m2)}{r^2} \quad (2)$$

m = MAGNETIC FIELD

(b) MAGNETIC FORCES



$$\text{FORCE } (F) = K3 \frac{(M1)(M2)}{r^2} \quad (3)$$

M = MASS

(c) GRAVITATIONAL FORCES

Figure 1 - Comparison of electric, magnetic and gravitational force relationships.

In Figure 1(c) the masses of the two bodies, M1 and M2 are located r distance apart, in meters. The resulting gravitational force is also measured in newtons, N.

All three formulas shown in Figure 1 are in the form of Coulombs Law which states that the force between two bodies varies directly with the product of their charges or mass and inversely with the square of the distances between them.

COULOMBS LAW

A typical application of Coulombs law for like electrostatic charges is shown below. Recall that like charges (either plus or minus) repel so that any positive answer indicates repulsion of the charges.

For example, a positive charge of 9×10^{-6} coulombs is located 0.03 meters from a second positive charge of 2×10^{-6} coulombs. The repelling force between the two charges is:

$$F = K\frac{(q1)(q2)}{r^2}$$

where F = force in newtons
q1, q2 = electrostatic charges in coulombs
r = separation between charges in meters

$$K = \text{constant } 9 \times 10^9 \frac{\text{N-m}^2}{\text{Coul}^2}$$

Substituting:

$$F = \left(9 \times 10^9 \frac{\text{N-m}^2}{\text{coul}^2}\right) \frac{(9 \times 10^{-6} \text{ coul})(2 \times 10^{-6} \text{ coul})}{(0.03 \text{ m})^2}$$

$$= \left(9 \times 10^9 \frac{\text{N-m}^2}{\text{coul}^2}\right) \frac{18 \times 10^{-12} \text{ coul}^2}{9 \times 10^{-4} \text{ m}^2}$$

Cancelling, we have

$$F = 18 \times 10^{-8} \times 10^9 \text{ N}$$

F = 180 newtons

Note that with both charges (q1, q2) the same polarity, the force, F, is positive indicating repulsion whereas if one charge were positive and the other negative, the forces would attract and the resultant force would be a negative quantity. As a matter of interest, a force of 1 newton is equal to 0.225 lbs. Thus, the 180 newtons indicated in the above problem would, in English units, be:

F = 180 X 0.225 lbs

F = 40.5 lbs

RESISTANCES

Different materials have different amounts of free electrons and therefore exhibit different amounts of opposition to current flow. This opposition is called RESISTANCE. The more free electrons available in a material the lower its resistance will be. The fewer free electrons a material has the higher its resistance will be.

Silver, gold and copper are good conductors having many free electrons at room temperature (25° C). Copper is the most widely used conductor while silver and gold are used for special applications only due to their high cost.

CROSS-SECTIONAL AREA

The CROSS-SECTIONAL area of a conductor greatly affects the conductor resistance. The greater the cross-sectional area of a conductor the greater number of free electrons available for electron flow and so the lower the resistance. Thus, a larger current will flow for a given applied voltage if the cross-sectional area is increased. This indicates that resistance is inversely proportional to the cross-sectional area of a conductor.

The DIAMETER of conductors used in electronics wiring is often only a fraction of an inch and is measured in mils (1/1000 of an inch). The cross-sectional AREA of the conductor is measured in CIRCULAR MILS, as shown in Figure 2.

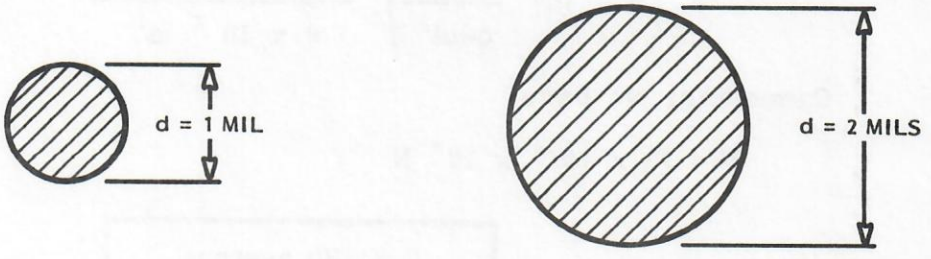


Figure 2 - Diameter and cross-sectional area.

The circular mils cross-sectional area of a wire is determined by squaring the diameter of the wire as measured in mils. Thus:

$$\text{circ-mils} = d^2 \qquad (4)$$

where circ-mils = circular mils
d = wire diameter in milli-inches

For example, given a wire that has a diameter of 0.03 inches find the cross-sectional area. Since 0.03 inches equals 30 milli-inches, we have

$$\text{circ-mils} = d^2$$

$$= 30^2$$

$$\boxed{\text{circ-mils} = 900}$$

Note that in Figure 2, doubling the diameter resulted in a four-fold increase in cross-sectional area.

CONDUCTOR LENGTH

The length of the wire conductor is also a factor which determines the resistance of the conductor. When the length of the conductor is increased, the number of collisions the free electrons encounter in the atomic structure as they move in the electron drift, increase proportionally. Because of the increased number of collisions more energy is given up in the form of heat. The additional energy loss results in a decrease in current flow for a given applied voltage. A decrease in current indicates an increase in resistance. You may conclude then, that an increase in conductor length causes a proportional increase in its resistance. Doubling the length of a wire doubles its resistance.

TEMPERATURE EFFECTS

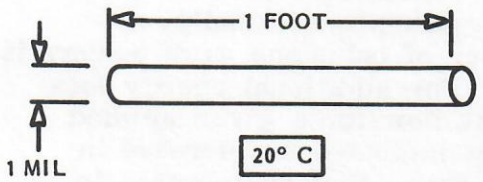
Temperature changes affect the resistance of conductors in different ways. Some materials increase their resistance when heated while some decrease their resistance. The amount of change in resistance per unit change in temperature is known as the TEMPERATURE COEFFICIENT. If a temperature increase causes a conductor's resistance to increase, it has a POSITIVE TEMPERATURE COEFFICIENT. In such materials a temperature increase causes additional quivering of the atoms creating increased numbers of collisions for the free electrons to increase resistance.

A material whose resistance decreases with a increase in temperature has a NEGATIVE TEMPERATURE COEFFICIENT. The resistance of such a material drops with an increase in temperature because more electrons are freed for conduction

by the heat than the increase in collisions by the quivering atomic structure. Most conductors have positive temperature coefficients but generally, that class of materials known as SEMICONDUCTORS, have negative temperature coefficients. (Typical are carbon, germanium and silicon.) Certain materials such as alloys of manganin and constantan, for example, have a ZERO TEMPERATURE COEFICIENT, that is, their resistance remains unchanged with variations in temperature.

SPECIFIC RESISTANCE

SPECIFIC RESISTANCE is a standard that has been developed to permit comparison of resistance characteristics of various conductors. The Specific Resistance of a material is the resistance, in ohms, offered by a one foot length, 1 mil in diameter, at 20° C as shown in Figure 3(a).



(a) CIRCULAR MIL FOOT

CONDUCTOR	OHMS PER CIRCULAR MIL FOOT
SILVER	9.8
COPPER	10.37
GOLD	14.7
ALUMINUM	17.02
BRASS	42.1
NICHROME	660.0

(b) SPECIFIC RESISTANCES

Figure 3 - The circular mil foot unit and typical values.

Each conductor material has its own value of specific resistance based on its molecular structure. The specific resistance of conductors often used in electronics is shown in the table in Figure 3(b).

The total resistance of a given length of wire can be expressed as: (ρ is greek letter rho pronounced "row.")

$$R = \rho \frac{L}{A} \qquad (5)$$

where R = resistance in ohms
ρ = specific resistance (ohms per circ-mil foot)
L = conductor length in feet
A = conductor cross-sectional area in circ-mils

For example, what is the resistance of 200 feet of copper wire, such as used for the Ed-Lab Trainer leads, having a cross-sectional area of 642 circular mils. Recall that the specific resistance of copper given in the table of Figure 3(b) is $\rho = 10.37$ ohms.

$$R = \rho \frac{L}{A}$$

$$= (10.37) \frac{200}{642}$$

200 FEET OF Ed-Lab COPPER LEAD WIRE	R = 3.23 ohms

STANDARD WIRE GAUGE SIZES

It is possible to manufacture wire with a diameter as small as one circular mil, increasing in diameter up to very large sizes in the area of 400 circular mils, in steps of 1 mil. In actual practice, wire diameters are made in a series of standard sizes which are assigned GAUGE numbers. The most commonly used system is the AMERICAN WIRE GAUGE which is shown in Table 1.

Column 1 of the Table lists the WIRE GAUGE number. The larger the number the smaller the diameter. The second column lists the wire DIAMETER in mils. Column 3 lists the CIRCULAR MIL area which is equal to the diameter squared. The last column lists the resistance of a 1,000 foot length of copper wire at 25° C.

1	2	3	4
Gauge number	Diameter, mils	Area, circular mils	Resistance, ohms per 1,000 ft, 25° C (77° F)
0000	460.0	212,000.0	0.0500
000	410.0	168,000.0	.0630
00	365.0	133,000.0	.0795
0	325.0	106,000.0	.100
1	289.0	83,700.0	.126
2	258.0	66,400.0	.159
3	229.0	52,600.0	.201
4	204.0	41,700.0	.253
5	182.0	33,100.0	.319
6	162.0	26,300.0	.403
7	144.0	20,800.0	.508
8	128.0	16,500.0	.641
9	114.0	13,100.0	.808
10	102.0	10,400.0	1.02
11	91.0	8,230.0	1.28
12	81.0	6,530.0	1.62
13	72.0	5,180.0	2.04
14	64.0	4,110.0	2.58
15	57.0	3,260.0	3.25
16	51.0	2,580.0	4.09
17	45.0	2,050.0	5.16
18	40.0	1,620.0	6.51
19	36.0	1,290.0	8.21
20	32.0	1.020.0	10.4
21	28.5	810.0	13.1
22	25.3	642.0	16.5
23	22.6	509.0	20.8
24	20.1	404.0	26.2
25	17.9	320.0	33.0
26	15.9	254.0	41.6
27	14.2	202.0	52.5
28	12.6	160.0	66.2
29	11.3	127.0	83.4
30	10.0	101.0	105.0
31	8.9	79.7	133.0
32	8.0	63.2	167.0
33	7.1	50.1	211.0
34	6.3	39 8	266.0
35	5.6	31.5	335.0
36	5 0	25 0	423.0
37	4.5	19.8	533.0
38	4.0	15.7	673.0
39	3.5	12.5	848.0
40	3.1	9.9	1,070.0

TABLE 1 - Standard solid copper wire table; American Wire Gauge (AWG).

CONDUCTANCE

Conductance is the ability of a conductor to pass electrons. Conductance is the opposite or reciprocal of resistance. Its symbol is G and

$$G = \frac{1}{R} \qquad (6)$$

The unit for conductance, G, is the Siemen, S. The old unit for G is the "mho," ohm spelled backwards. The symbol often used to indicate conductance is an inverter omega, ℧.

The factors that affect the magnitude of resistance are the same for conductance but they affect conductance in the opposite manner. Therefore, if

$$R = \frac{\rho L}{A}$$

then

$$G = \frac{A}{\rho L} \qquad (7)$$

where R = resistance in ohms
G = conductance in S (mho)
ρ = specific resistance of the material
L = length of the conductor in feet
A = cross-sectional area in circ-mils

When the resistance of a material is known, taking its reciprocal will give its conductance. Also, if conductance is known, taking its reciprocal will give the resistance.

For example, if 200 feet of No. 22 copper wire used for the Ed-Lab Trainer leads is 3.23 ohms, the conductance is:

$$G = \frac{1}{R} = \frac{1}{3.23}$$

G = 0.31 siemens

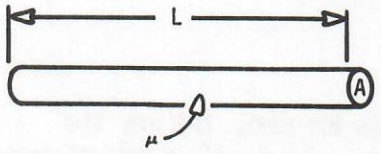
RELUCTANCE

PERMEABILITY, designated by the Greek letter μ, is a measure of the ease with which a material can conduct magnetic lines of force. The permeability rating of material is relative to air which is used as the standard and has an assigned value of 1. Thus the μ of a material is based on

$$\mu = \frac{\text{number of flux lines per unit area in the core material}}{\text{number of flux lines per unit in an air core}} \qquad (8)$$

RELUCTANCE, $\mathcal{R}$, in a magnetic circuit is the equivalent of resistance in an electrical circuit. Reluctance was discussed in Information Sheet 2. The reluctance of a material varies with its length and cross sectional area. The reluctance increases as the length of the magnetic conductor is increased and decreases as the cross sectional area is increased. The value of $\mathcal{R}$ is also affected by the μ of the material. The higher the μ the lower the reluctance will be. This magnetic resistance is shown mathematically by an equation similar to that for electrical resistance.

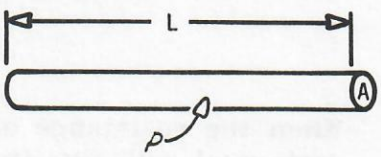
MAGNETIC CIRCUIT



$$\mathcal{R} = \frac{L}{\mu A}$$

where $\mathcal{R}$ = Reluctance
L = core length in in.
A = cross-section area, in^2.
μ = permeability rating

ELECTRICAL CIRCUIT



$$R = \frac{\rho L}{A}$$

where R = Resistance
L = conductor length in feet
A = cross-sectional area, circ-mils
ρ = specific resistance rating

CONCLUSIONS

We have learned from this information sheet that:

The force between two static charges can be calculated from

$$F = K \frac{(q1)(q2)}{r^2}$$

The force between two magnetic fields can be calculated from

$$F = K \frac{(m1)(m2)}{r^2}$$

The gravitational force between two masses can be calculated from

$$F = K \frac{(M1)(M2)}{r^2}$$

All of the above equations are forms of Coulomb's Law.

Different metals have different values of resistance for the same diameter and length.

Copper is the most widely used electrical conductor.

The resistance of a conductor is inversely proportional to its cross-sectional area.

The cross-sectional area of a conductor is equal to the diameter squared.

When the diameter of a conductor is doubled the cross-sectional area increase by four times.

When the cross-sectional area increases by four times, the resistance of the conductor decreases to one fourth.

The length of a conductor and its resistance are directly proportional. Doubling the length doubles the resistance.

The resistance of most conductors changes with temperature.

When resistance increases with temperature the conductor has a Positive Temperature Coefficient.

When the resistance of a conductor decreases with temperature, it has a Negative Temperature Coefficient.

Material whose resistance remains unchanged with temperature variations has a Zero Temperature Coefficient.

The Specific Resistance of a conductor is that which is exhibited by a one foot length of the conductor with a 1 mil diameter.

The resistance of a conductor is equal to

$$R = \rho \frac{L}{A}$$

Standard wire diameters are specified by Gauge numbers from the American Wire Gauge table (AWG).

The conductance of a wire is a measure of its ability to conduct current and is the opposite of resistance.

Conductance is equal to 1/R, is symbolized by G, measured in siemens, S, and is sometimes called mhos and shown as $\mho$.

ASSIGNMENT

Answer the following true-false questions.

1. The force between two electrical charges will reduce by one fourth when the space between them is doubled. ____

2. The force between two magnetic fields can be calculated using the same formula as for the electrical forces only if the permeability of the medium in which the magnets are located is air or a vacuum. ____

3. The diameter of one copper wire is double the diameter of a second copper wire of the same length. One of the wires has a resistance one half of the other. ____

4. A length of copper wire has a resistance of 50 ohms. If the diameter of the wire and its length are doubled the new resistance will be 25 ohms. ____

5. A wire has a diameter of 0.003 inches. Its cross-sectional area is equal to 0.003^2. ____

6. A length of material has a resistance of 1500 ohms at 25° C. If, as the material is heated, the resistance rises to 1600 ohms, it is said to have a Positive Temperature Coefficient. ____

7. If, when heated, the resistance of a material drops, it is most likely a semiconductor. ____

8. Given that brass has a specific resistance of 42.1 ohms, a one mil diameter brass wire, 3 feet long will have a resistance of 126.3 ohms. ____

9. A resistance of 1,000 ohms has a conductance of 0.001 S. ____

10. A conductance of 10 microsiemens has a resistance of 10,000 ohms. ____

KEY TERMS

1. CONDUCTANCE

   The ability of a conductor to pass electrons. It is the reciprocal of resistance, its symbol is G and its unit is siemens, S.

2. CROSS-SECTIONAL AREA

   The area of a conductor cut at right angles to its length. It is measured in square inches or circular mils.

3. RELUCTANCE

   A measure of the opposition of a material to the flow of magnetic lines of force. The equivalent of electrical resistance; the opposite of permeability.

4. SPECIFIC RESISTANCE

   The resistance of 1 foot of material, 1 mil in diameter at 20° C. Used as a standard to compare the resistance characteristics of different materials.

5. TEMPERATURE COEFFICIENT

   The change in resistance of a material per unit change in temperature. When resistance increases with temperature it is a Positive Temperature Coefficient. A decrease in resistance for an increase in temperature is a Negative Temperature Coefficient.

6. WIRE GAUGE

   The wire diameter as specified by a number. The number is listed in a Wire Gauge Table and indicates diameter, cross-sectional area, resistance per given length and other data. The smaller the gauge number (0000) the larger the wire diameter.

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Text-Lab Manual
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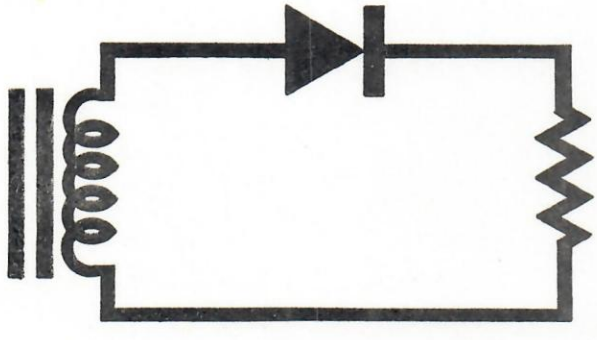

H1

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Ed-Lab
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DIODES and POWER SUPPLIES
PART H1

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ISBN 0-86711-182-8
Printed in the United States of America

CES INDUSTRIES, INC.
Educational Products Division
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Farmingdale, New York 11735
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PART H1 - DIODES and POWER SUPPLIES

Table of Contents

		Student Progress Record and Guide
		Safety Notes
Info. Sheet	1	Solid State PN Junctions
Experiment	1	Diode Characteristic Curve Plot
Experiment	2	Rectifier Circuits
Info. Sheet	2	Diode Characteristic Oscilloscope Display
Experiment	3	Half-wave Rectifier Circuit Operation
Experiment	4	Full-wave Rectifier Circuit Operation
Info. Sheet	3	Power Supply Filter Circuits
Experiment	5	Filter Circuit Operation
Experiment	6	Diode Peak Repetitive and Surge Currents
Info. Sheet	4	Voltage Multiplier Circuits
Experiment	7	Voltage Multiplier Circuit Operation
Info. Sheet	5	Diode Testing and Troubleshooting
Experiment	8	Power Supply Troubleshooting

In this manual, all Information Sheets are given in the Text section, and all experiments then follow in the Lab section. The above list is the general order for which the Information Sheets are referred.

Name _____

Class _____

STUDENT PROGRESS RECORD & GUIDE FOR PART H1

EXP./INFO.	TITLE	ASSIGNMENT		GRADE
		DATE DUE	DATE SUBMITTED	
Info. Sheet 1	Solid State PN Junctions			
Experiment 1	Diode Characteristic Curve Plot			
Experiment 2	Rectifier Circuits			
Info. Sheet 2	Diode Characteristic Oscilloscope Display			
Experiment 3	Half-wave Rectifier Circuit Operation			
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Experiment 5	Filter Circuit Operation			
Experiment 6	Diode Peak Repetitive and Surge Current			
Info. Sheet 4	Voltage Multiplier Circuits			
Experiment 7	Voltage Multiplier Circuit Operation			
Info. Sheet 5	Diode Testing and Troubleshooting			
Experiment 8	Power Supply Troubleshooting			

Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part E1 and G1. Review this lesson.

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PART H1

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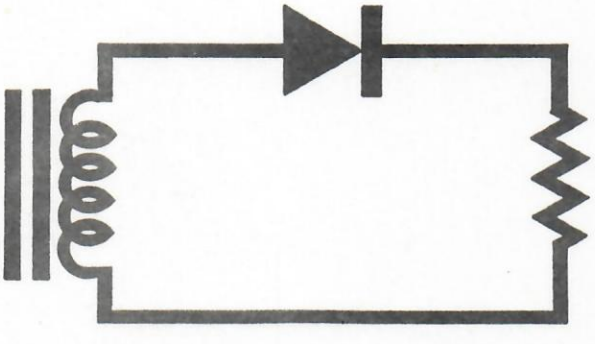
H1-DIODES and POWER SUPPLIES



H1

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PART H1

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ISBN 0-86711-176-3
Printed in the United States of America

CES INDUSTRIES, INC.
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Farmingdale, New York 11735
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PART H1 - DIODES and POWER SUPPLIES

Table of Contents

INFORMATION SHEETS

1. Solid State PN Junctions
2. Rectifier Circuits
3. Power Supply Filter Circuits
4. Voltage Multiplier Circuits
5. Diode Testing and Troubleshooting

Ed-Lab
Text Manual
DIODES and POWER SUPPLIES
PART H1

Solid State PN Junctions

Info Sheet 1

Objectives

When you finish this information sheet, you will be able to:

1. Describe the atomic structure of silicon and germanium.
2. Explain how valence electrons are shared by adjacent atoms.
3. Define what is meant by covalent bonding.
4. Explain the need for and the process of doping semiconductor materials.
5. List several typical pentavalant and trivalent dopants.
6. Describe what is meant by P-type and N-type materials.
7. Explain how the barrier potential develops across a PN junction.
8. Explain the operation of a PN junction when forward and reverse biased.
9. Define Majority and Minority current carriers.
10. Draw the diode characteristic curve on a four quadrant graph.
11. Calculate the forward resistance of a diode.
12. Define Peak Inverse Voltage and explain the Avalanche process.

Discussion

In the basic studies of dc and ac circuits, the electrical components discussed were batteries, switches, lamps, resistors, capacitors, inductors and transformers. These devices determined the voltages and currents in an electrical circuit based on Ohm's Law and Kirchhoff's Laws. In some of the previous

demonstration experiments, two other components were used; these were the DIODE and the TRANSISTOR. It was indicated that the diode was basically a "one way valve" for electron current flow, unlike the other components in which electrons could flow in two directions.

This unit of study is concerned with the theory of operation of the solid state diode and its applications in circuits.

The transistor is, basically, also a "one way valve" for current flow, but we can control the *amount* of current flow. The transistor will be studied in the next unit, J1. The schematic symbols for the diode and transistor are shown in Figure 1.

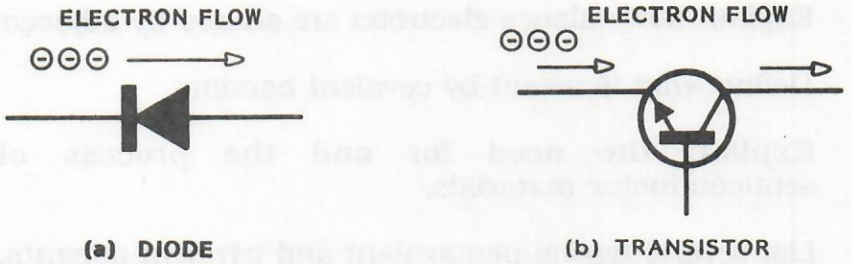


Figure 1 - Schematic symbols for a diode and transistor.

Historical Background

Up to 1947, virtually all electronic circuit functions were accomplished using vacuum tubes. In 1947 Messrs. Bardien, Brittain and Shockley, at Bell Laboratories, made the first operating solid state transistors. The early transistors showed such great promise that an enormous amount of research was done. Within less than five years, useable transistors were available and the "Solid State" era was in full swing. Figure 2 shows a relative size comparison between the early vacuum tubes, a solid state diode, a transistor and a modern integrated circuit (IC).

Vacuum tubes are so-called because their operating elements are contained in a glass or metal enclosure that has all the air and gasses removed leaving a vacuum. Transistors require no vacuum to operate as they are made from solid blocks of material. Because of this they are called "Solid State" devices. While transistors are used to amplify or strengthen weak signals, the diode has other purposes. Before we can begin to understand the operation of solid state diode or transistor devices, we must first understand the nature of the materials used to make them.

Semiconductor Materials

The electrical characteristics of a semiconductor material fall between those of conductors and insulators. The atoms of a good conductor have valence rings that contain one electron and the

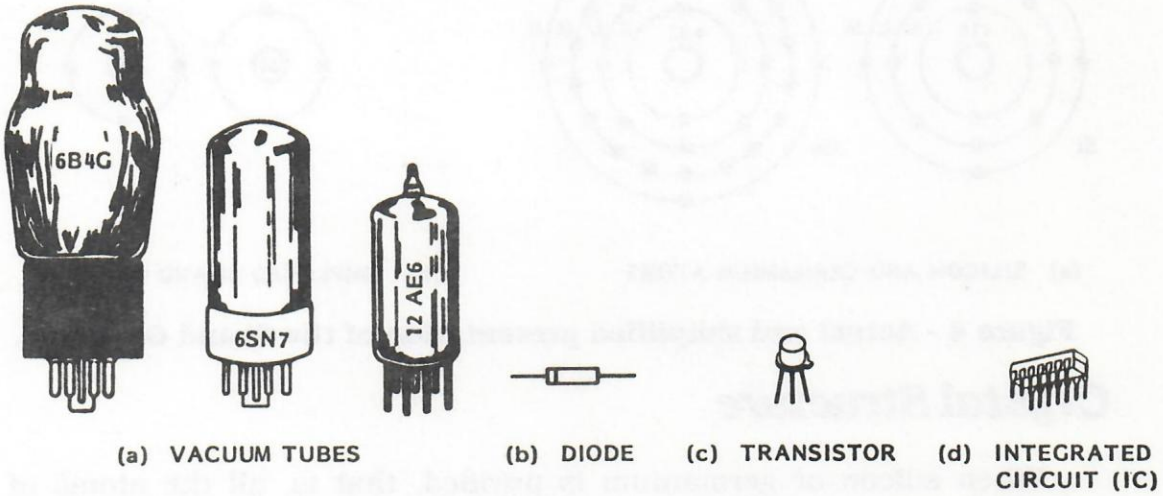


Figure 2(a) - Gradual size reduction in vacuum tubes. (b) - Diode. (c) - The tiny transistor and (d) an IC that contains hundreds of transistors and diodes.

valence ring (the outer ring of electrons) of an atom in an insulator contains eight electrons. A semiconductor falls between a conductor and an insulator with a valence ring of four electrons, as shown in Figure 3(c).

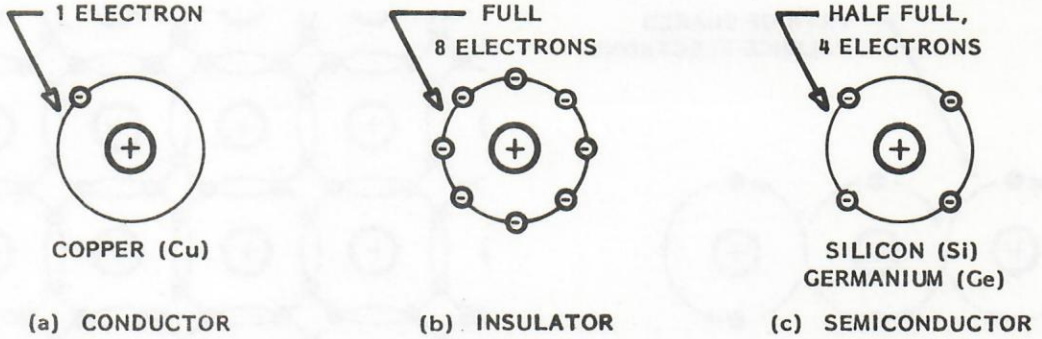
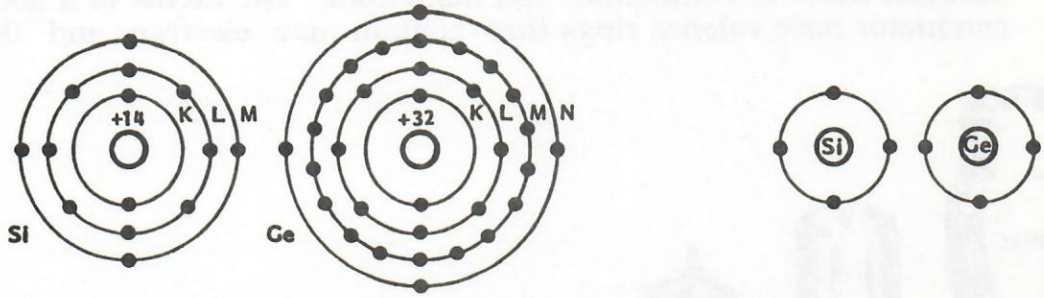


Figure 3 - Valence ring electrons for conductors, insulators and semiconductors.

The two semiconductor materials most often used are Germanium (Ge) and Silicon (Si). The molecular structures of these elements are shown in Figure 4(a). Since the electrons in the valence ring

are the only ones of interest to us, we can simplify the drawings of the two atoms to that shown in Figure 4(b). The inner shells or rings are simply understood to exist though not shown.

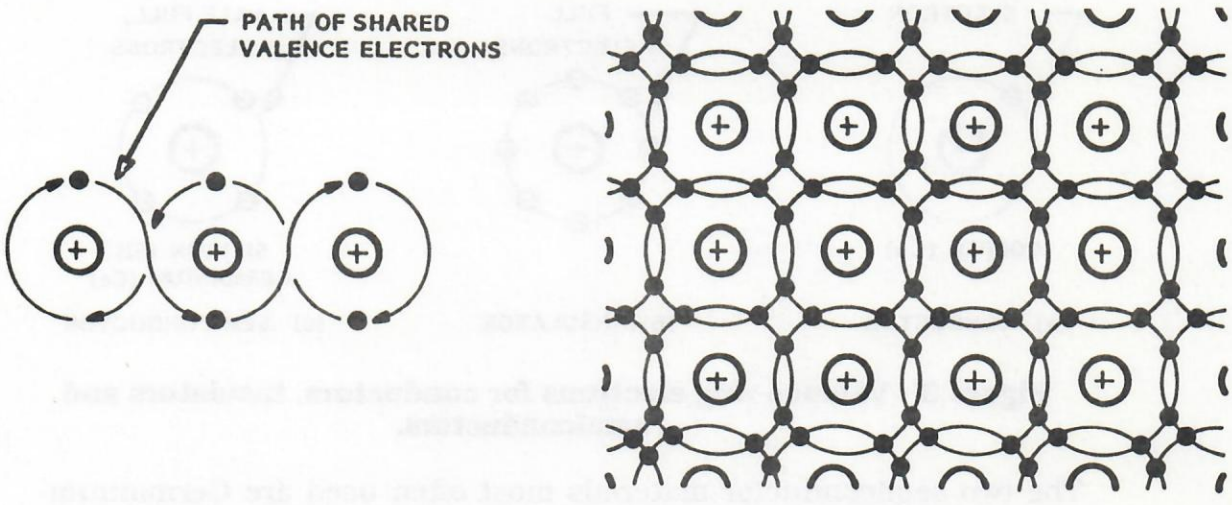


(a) SILICON AND GERMANIUM ATOMS (b) SIMPLIFIED SI AND GE ATOMS

Figure 4 - Actual and simplified presentation of the Si and Ge atoms.

Crystal Structure

When silicon or germanium is purified, that is, all the atoms of other materials are removed, it is defined as INTRINSIC material. Silicon and germanium, in their intrinsic form, behave more like insulators than semiconductors. The reason for this can be understood by examining Figures 5(a) and (b). In its pure, state silicon contains only silicon atoms with four valence electrons. Since each atom in the structure desires eight electrons in the valence ring for the greatest stability, they borrow or share valence electrons from adjoining atoms.



(a) SHARED ELECTRON PATH (b) RESULTING CRYSTAL STRUCTURE

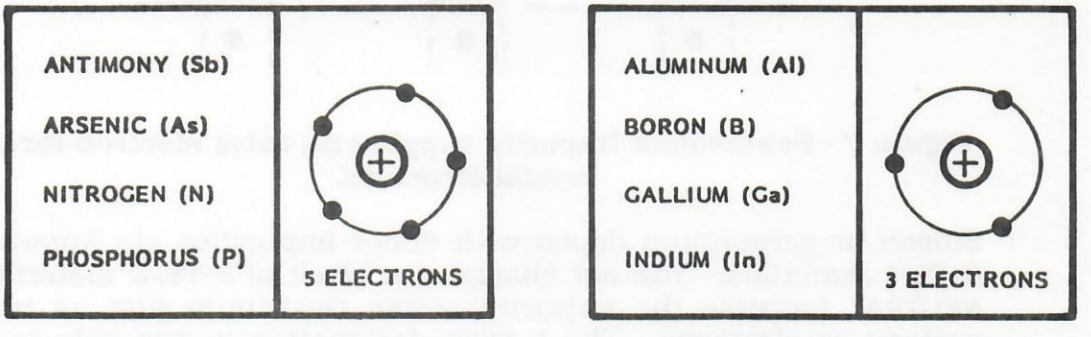
Figure 5(a) - Shared valence electrons. (b) - Crystal lattice structure of pure Si or Ge.

The manner in which electrons are shared by adjoining valence rings is shown in Figure 5(a). If one atom shares one valence electron from four adjoining atoms, for that one instant, the atom has eight valence electrons. As all the atoms share their valence electrons, a crystal structure is formed that is more like an insulator than a semiconductor as shown in Figure 5(b). The process of sharing valence electrons is known as COVALENT BONDING, SHARING BONDS OR ELECTRON PAIR BONDING.

Doping

Intrinsic silicon and germanium act as insulators and as such are of little use. In order for these materials to be useful as semiconductors, it is necessary to add very specific impurities in carefully controlled amounts (one part impurity to 1 billion or 10^9 parts Si or Ge). The addition of these impurities to the silicon or germanium is called DOPING. Two types of material are formed by the doping process, one with an excess of electrons in the crystal structure and another with a shortage of electrons in the crystal structure.

Some of the more common impurities used to dope semiconductors are shown in Figure 6. Since only the valence ring of the impurity atom is of importance, that is all that is shown. It is important to understand that each impurity atom has a full count of electrons and an equal number of protons in its nucleus so that each atom is neutral, that is, not ionized plus or minus. Observe that the impurities in Figure 6(a) have five valence electrons and are called PENTAVALENT materials. Group (b), with three valence electrons, are called TRIVALENT materials.



(a) PENTAVALENT (DONOR) IMPURITIES (b) TRIVALENT (ACCEPTOR) IMPURITIES

Figure 6 - Impurities used for doping Si and Ge.

N-Type Materials

When a pentavalent impurity atom is added to intrinsic silicon or germanium, only four of the impurity valence electrons are able to form covalent bonds. The fifth valence electron, which is unable to lock into the structure, is free to wander through the crystal. This is shown in Figure 7. Observe that the impurity, Arsenic (As), is locked in and does not wander; only the extra electron that cannot lock in, wanders. Since the pentavalent impurities donate an extra electron to the crystal structure they are called DONOR IMPURITIES.

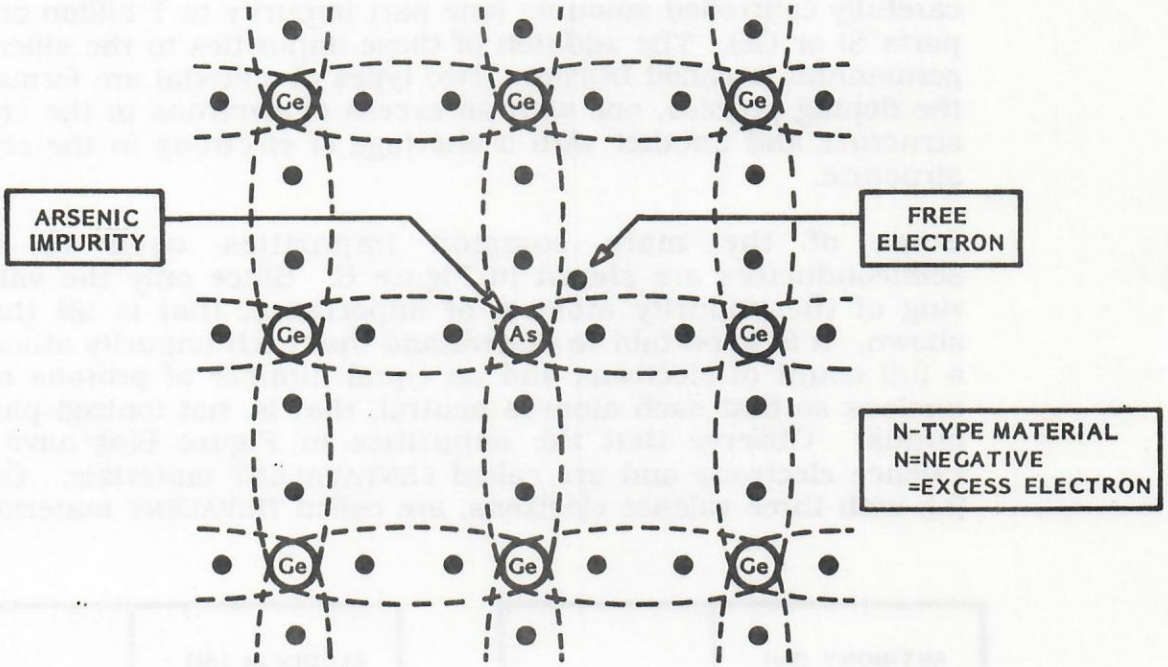


Figure 7 - Pentavalent impurity supplies an extra electron for the crystal structure.

Silicon or germanium doped with donor impurities are known as N-TYPE materials. The net charge of a block of N-TYPE material is *NEUTRAL* because the impurity atoms contribute just as many protons as electrons. The N-TYPE designation is due only to the electrons that cannot lock into the crystal structure.

When placed in an electrical circuit, the N-type material shown in Figure 8 acts as a poor conductor. The free electrons, those not bound into the crystal structure, provide the electrons for current flow just as the free electrons in copper.

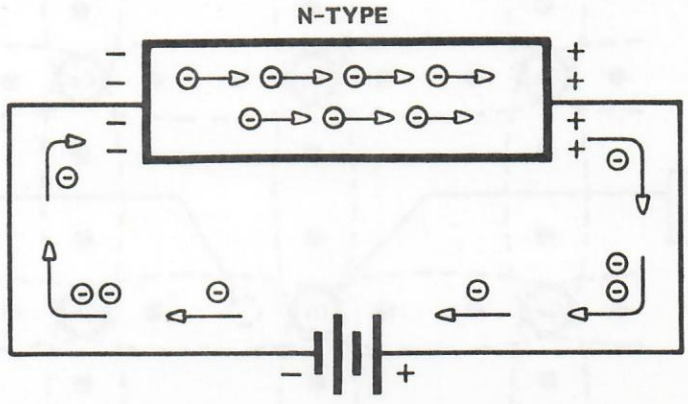


Figure 8 - Electron flow through N-type material.

The electron flow is the normal movement of electrons from the negative terminal of the voltage source, through the N-type material and back to the positive terminal of the source. The free electrons in the semiconductor are repelled from the negative terminal and attracted by the positive terminal of the source.

P-Type Materials

The impurity materials listed in group (b) of Figure 6 have three electrons in the valence ring and are called TRIVALENT elements. When Indium (In), a trivalent material, is mixed with intrinsic silicon or germanium, the impurity atoms lock into the crystal structure as shown in Figure 9.

Since the impurity atom has only three donor electrons in its valence ring it leaves a *HOLE* in the crystal structure of the germanium (Figure 9). The hole represents a break or an incomplete covalent bond and the "hole" has an attraction for any free electron to fill the space. For this reason, a trivalent impurity is known as an ACCEPTOR. Because materials doped with trivalent impurities accept or "attract" electrons, they are known as P-TYPE materials. The hole is easily filled with an electron that is released from a nearby atom which then leaves a hole in the second atom. The net effect is that the holes appear to be "drifting" in the P-type material just as the electrons drifted in the N-type material. It is these holes which provide the current flow (current carriers) in the P-type material. A hole can be indicated in a diagram as a circle with a plus sign inside indicating that it will "attract" or accept an electron.

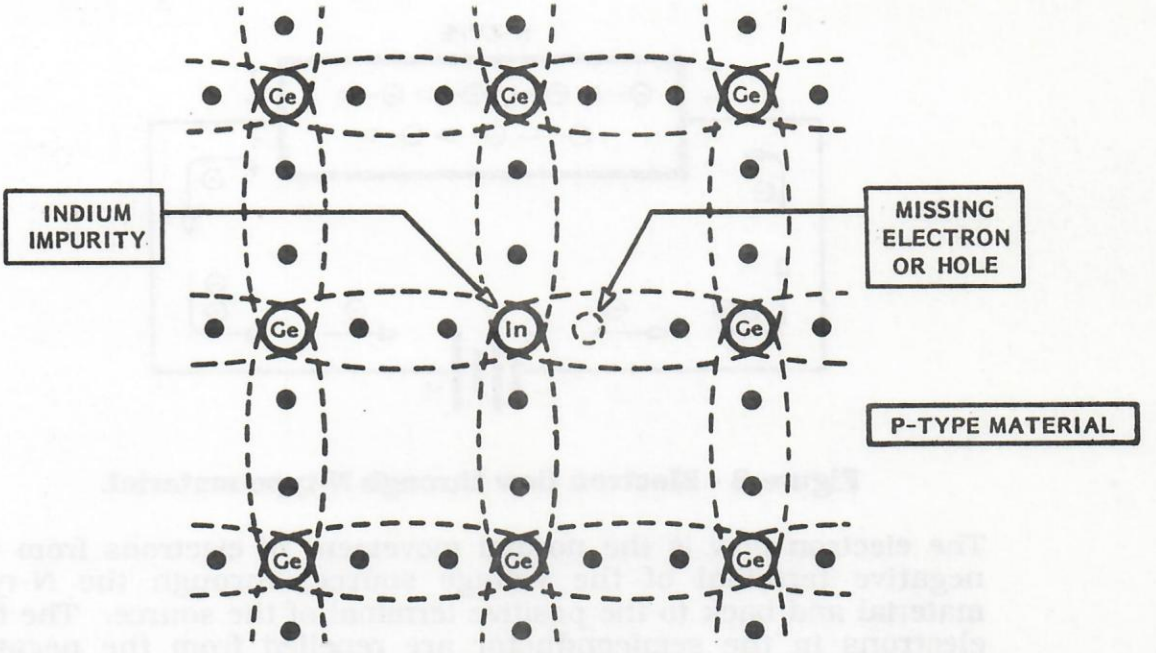


Figure 9 - Trivalent impurity creates a hole or a "missing electron" in the crystal structure.

The net charge of P-type materials is also neutral since the impurity contributes as many protons to the intrinsic material as it does electrons.

When a voltage is applied across a block of P-type material, there are no free electrons available to act as current carriers. The holes are spaces for electrons and since they are seeking electrons (negative charges) the holes are considered to be positive and they are attracted to the negative terminal of the voltage source as shown in Figure 10.

As the electrons enter the P-type material they move from hole to hole as they enter the drift through the semiconductor. The holes appear to be drifting towards the negative terminal, away from the positive terminal in the semiconductor material. For P-type material the current carriers are considered to be HOLES but in the external circuit, the current carriers are electrons.

Majority and Minority Carriers

When intrinsic germanium and silicon are prepared in the manufacturing process, the aim is 100% purity - a perfect crystal. Even Ivory Soap, however, only promised 99 and 99/100 % purity and the same is true of Si and Ge; some impurities always remain.

These impurities, other than the inserted "donors," are of both types, those that contribute holes and those that contribute extra electrons.

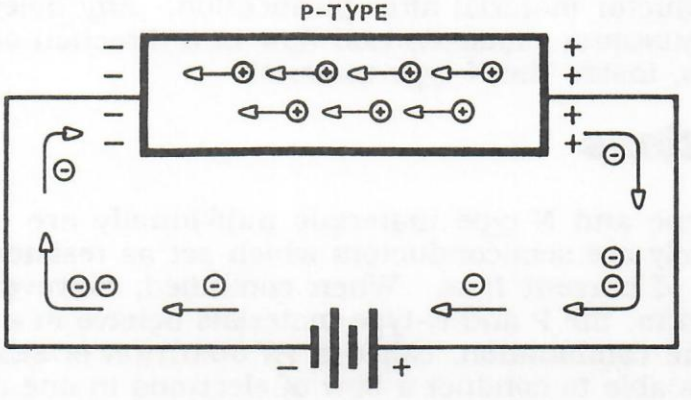


Figure 10 - Hole flow in the P-type material.

In P-type materials, conduction takes place through the holes formed by doping. Any holes provided by the left-over impurities simply join the flow. The holes are known as the MAJORITY CARRIERS. The electrons that remained from the undesired impurities, flow in the opposite direction through the P-type material as shown in Figure 11(a). Since there are so few free electrons in the P-type material, they are known as MINORITY CARRIERS.

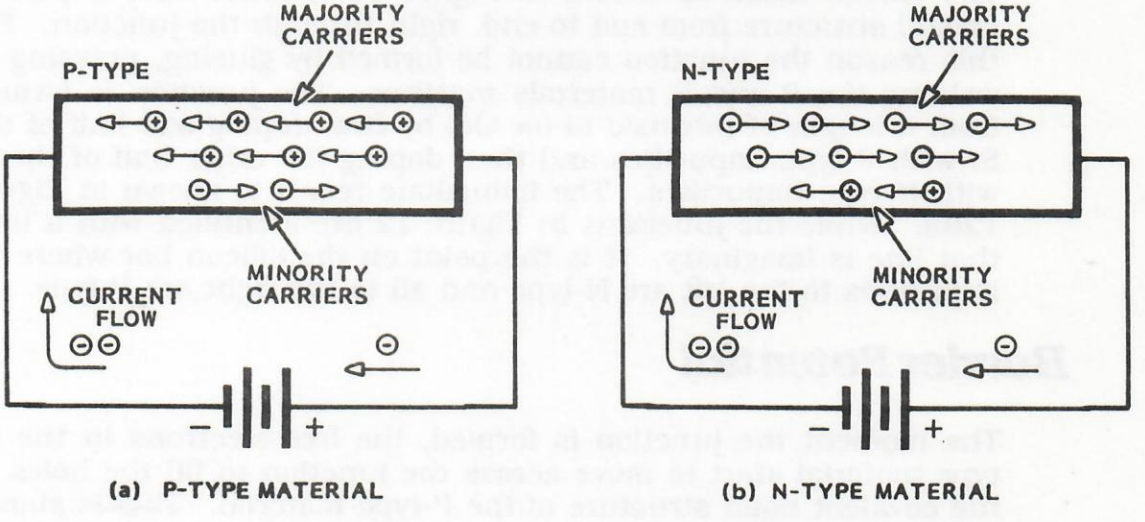


Figure 11 - Majority and minority carriers in P and N-type material.

In the N-type material, shown in Figure 11(b), the MAJORITY CARRIERS are the electrons introduced by the pentavelant impurities as well as those few impurities that remained in the semiconductor material after purification. Any holes that remain are the MINORITY CARRIERS and flow in a direction opposite to the electrons, inside the N-type material.

PN Junctions

The P-type and N-type materials individually are of limited use and merely are semiconductors which act as resistors to limit the amount of current flow. When combined, however, in a single crystal form, the P and N-type materials behave in a very unusual way. The combination, called a PN JUNCTION or SEMICONDUCTOR DIODE, is able to conduct a flow of electrons in one direction only. A basic PN junction is shown in Figure 12.

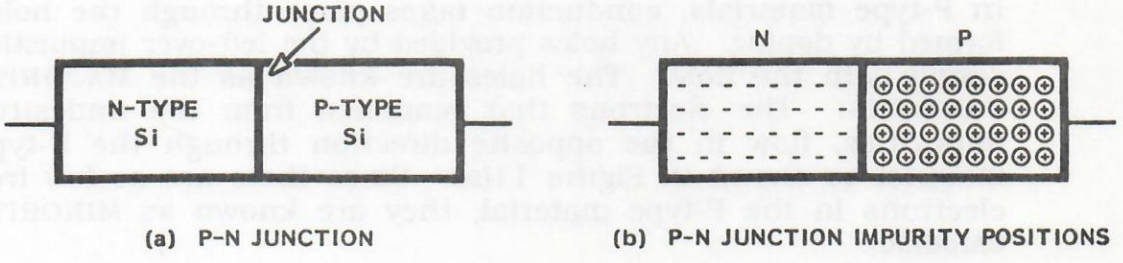


Figure 12(a) - PN junction. (b) - Impurity distribution.

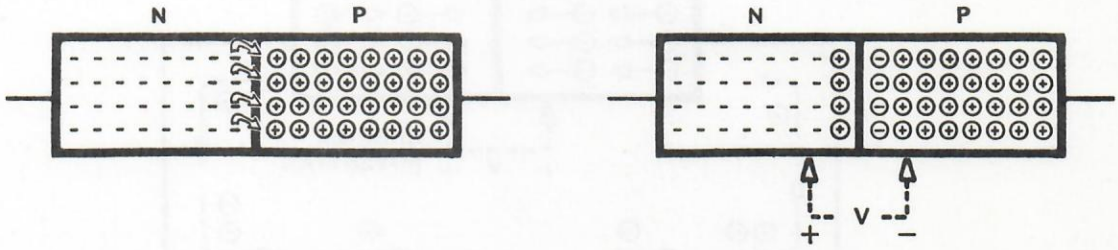
The silicon material shown in Figure 12(a) must have a perfect crystal structure from end to end, right through the junction. For this reason the junction cannot be formed by glueing, pressing or welding the P and N materials together. The junction is formed from a length of intrinsic Si (or Ge) by first doping one half of the Si with P-type impurities and then doping the other half of the Si with N-type impurities. The immediate result is shown in Figure 12(b). While the junctions in Figure 12 are identified with a line, that line is imaginary. It is the point on the silicon bar where all impurities to the left are N-type and all to the right are P-type.

Barrier Potential

The moment the junction is formed, the free electrons in the N-type material start to move across the junction to fill the holes in the covalent bond structure of the P-type material. This is shown in Figure 13(a).

If the process shown in Figure 13(a) continued, all the free electrons in the N-type material would move into the P-type material and fill all the holes. The result would be a bar of stable silicon (or Ge) that would act as an insulator.

What actually does happen is that the free electrons closest to the junction move across the junction and fill those holes in the covalent bonding structure that are also close to the junction. As the electrons leave the N-type material, the neutral electrical balance of the N-type material is upset. There are now more protons than electrons in the N-type material so it assumes a NET POSITIVE CHARGE. The P-type material, having accepted electrons into the holes adjacent to the junction, now has more electrons than protons and shows a NET NEGATIVE CHARGE.



(a) ELECTRON MOVEMENT (b) BARRIER POTENTIAL

Figure 13 - Electron movement across junction.

Electrons will continue to cross the junction from the N to P-type areas until the negative charge on the P-type material builds up to a level strong enough to stop the electron movement. Recall that electrons are negative charges that are repelled by a negative potential. Because of this, the initial movement shown in Figure 13(a) stops. Note that in Figure 13(b), one side of the junction has an excess of electrons (P side) and the N side has a *shortage* of electrons. A difference of potential now exists across the junction that bars a further migration of electrons and for this reason it is called the BARRIER POTENTIAL.

Forward Biased Junction

When the polarity of an external voltage source is connected to a PN junction as shown in Figure 14, the diode is said to be FORWARD BIASED. Electrons leave the negative terminal of the voltage source, flow into the N-type material and repel or force the free electrons toward the junction.

Similarly, the positive terminal of the source, connected to the P-type material repels the holes and drives them toward the junction. At the junction, the electrons combine with the holes. The result is that for each electron that enters the N material, on electron exits from the P material to flow to the positive terminal of the source.

Note that the external voltage source is opposite in polarity to the barrier potential and "overcomes" it thus permitting electron flow across the junction. If the externally applied voltage across the diode is less than the barrier potential, then no current will flow. The diode is, therefore, not a perfect or "ideal" one way valve.

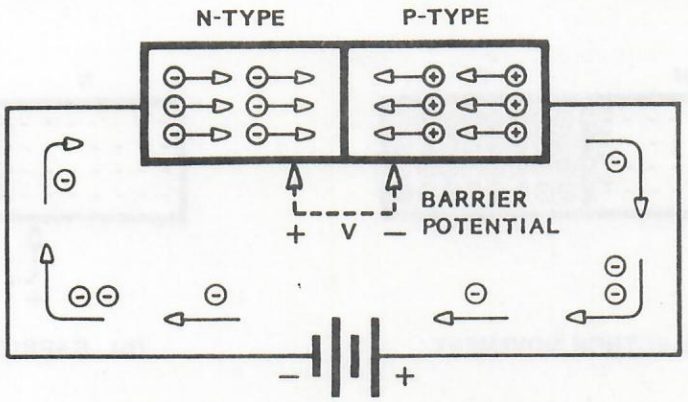


Figure 14 - Forward biased PN junction.

Reverse Biased Junction

Figure 15 shows the external voltage source connected across a PN junction with the positive terminal connected to the N-type material and the negative to the P-type material. Wired in this manner, the source voltage reinforces the barrier potential and no electrons flow across the junction.

As shown in Figure 15, the electrons are drawn away from the junction to the far end of the N-type material by the positive terminal of the voltage source. The holes in the P-type material are drawn away from the junction to the other end, attracted by the negative polarity of the source voltage.

The area around the junction is DEPLETED of current carriers (electrons and holes) and is called the DEPLETION REGION. Any material that has no current carriers is an insulator and so, when reversed biased there should be no current flow across the PN junction. This explains why a semiconductor diode does not conduct in the "reverse" direction.

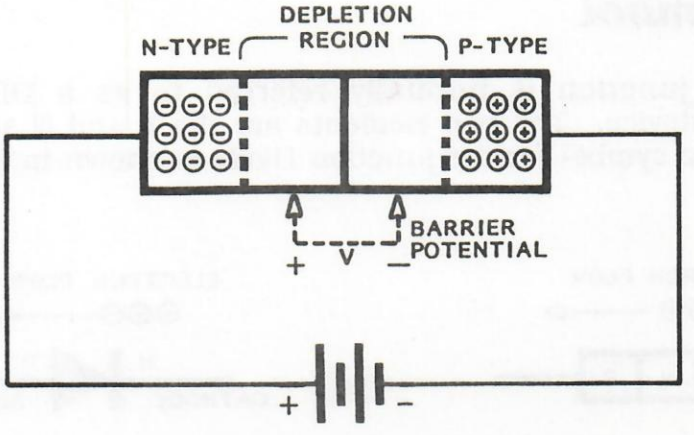


Figure 15 - Reverse biased PN junction.

Leakage Current

It was stated earlier that there are MINORITY current carriers in both the P and N-type materials as shown in Figure 16.

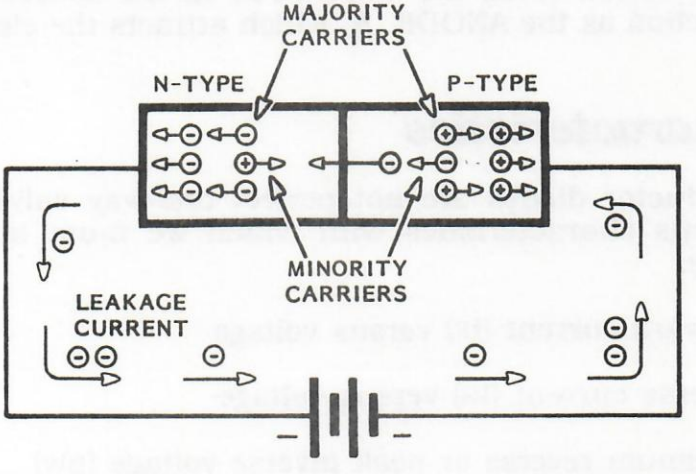


Figure 16 - Leakage current flow in a reverse biased P-N junction.

When the PN junction is reversed biased, no majority carriers flow across the junction. The PN junction is, however, *FORWARD BIASED* for any minority carriers in the P and N materials. This results in a very small current flow when in the reverse biased state which is defined as LEAKAGE CURRENT. The less leakage a diode has the better. Silicon diodes have much less leakage than germanium diodes.

Diode Symbol

The PN junction is normally referred to as a DIODE, a two element device. The two elements are the P and N sections. The schematic symbol for the junction Diode is shown in Figure 17.

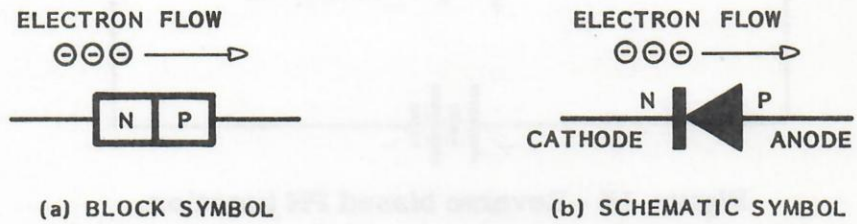


Figure 17 - Diode symbol and electron flow direction.

The direction of electron flow is opposite to the arrow symbol of the diode. The arrowhead represents the P material and the bar represents the N material. The arrow does, however, point in the direction of the flow of positive charges. Also, the bar of N section is often referred to as the CATHODE, K, the source of electrons and P section as the ANODE, A, which attracts the electrons.

Diode Characteristics

Semiconductor diodes are not perfect one-way valves and there are various characteristics with which we must be concerned. These are:

a. Forward current (I_F) versus voltage

b. Reverse current (I_R) versus voltage

c. Maximum reverse or peak inverse voltage (piv)

d. Maximum allowable forward current (I_F max)

e. Static (dc) diode resistance

f. Dynamic (ac) diode resistance

g. Non-linear diode junction resistance

h. Diode reverse recovery time (trr)

When forward biased, a diode offers a very low resistance to the flow of current. The plot of the forward characteristics of a silicon diode is shown in Figure 18.

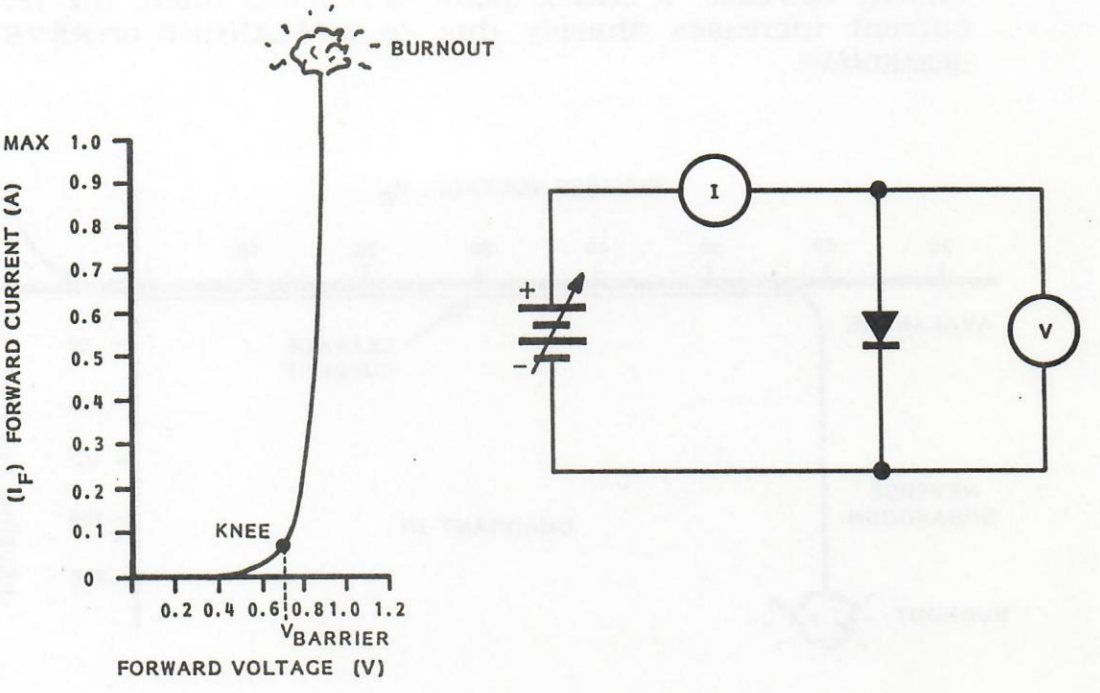


Figure 18 - Typical forward characteristics of a silicon diode and the circuit used to plot it.

As shown, there is no forward current flow until the forward voltage rises high enough to overcome the barrier potential, approximately 0.3 volts for Ge and 0.7 volts for Si. A further increase in forward voltage causes an exponential rise in current and then, after the area called the KNEE of the curve, the current rises steeply for a slight increase in forward voltage. For the diode shown in Figure 18, the maximum forward current is 1 ampere and, when exceeded will cause the diode to burn out.

Reverse Bias Characteristics

Were it not for the impurities remaining in the semiconductor material after purification, a reverse biased diode would permit absolutely no current flow. Because of the minority carriers there is an undesired LEAKAGE CURRENT as illustrated in Figure 19, the plot of the reverse voltage versus the reverse current. A very low current flows because there are so few minority current carriers.

As the reverse voltage increases, there is no increase in current because all the carriers available are already in the flow. Increasing the reverse voltage further does increase the VELOCITY of the minority current carriers. As the reverse voltage and the velocity increase, a critical point is reached where the reverse current increases sharply due to AVALANCHE or REVERSE BREAKDOWN.

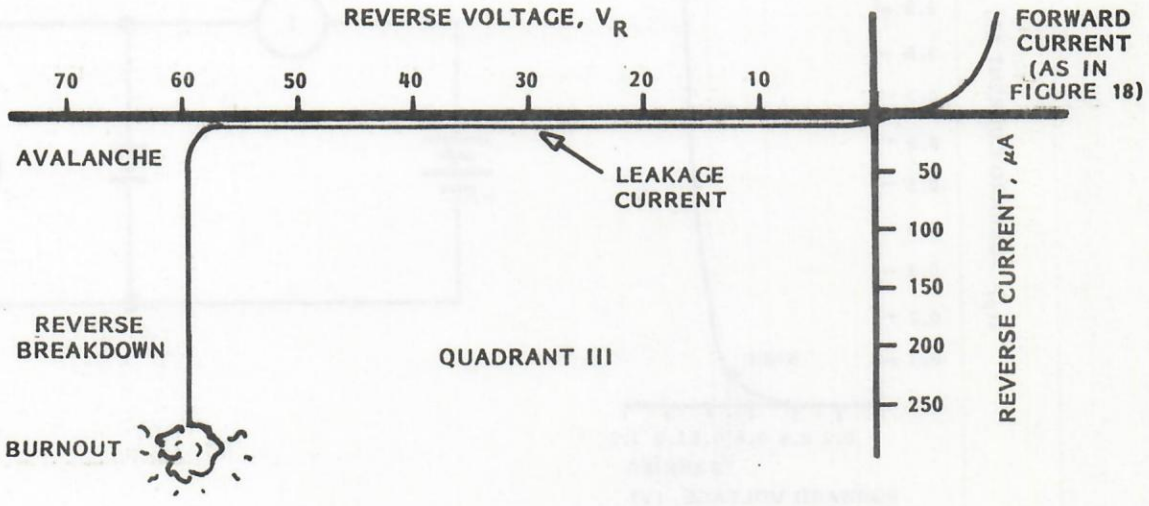


Figure 19 - Reverse characteristics of a silicon diode.

Observe that the reverse characteristics in Figure 19 are drawn in the third quadrant of a four quadrant graph. Also, the voltage and current scale calibrations are very different (I is low and V is high) from the forward quadrant, I.

Avalanche

The AVALANCHE or breakdown, discussed above, occurs in a diode when the reverse voltage is high enough to accelerate the minority carriers so that they collide violently with valence electrons of the atoms in the junction area. The collisions impart sufficient energy to the valence electrons to cause them to break loose and join the current flow. The freed electrons, in turn, strike more valence electrons and break them loose. The effect, if permitted to continue, produces a sudden and enormous increase in reverse current after the critical point is reached. Avalanche, as illustrated in Figure 20, shows the effect of a single minority current carrier (an electron) striking a silicon atom and freeing a single electron. This results in two free carriers which then become four, eight and so on.

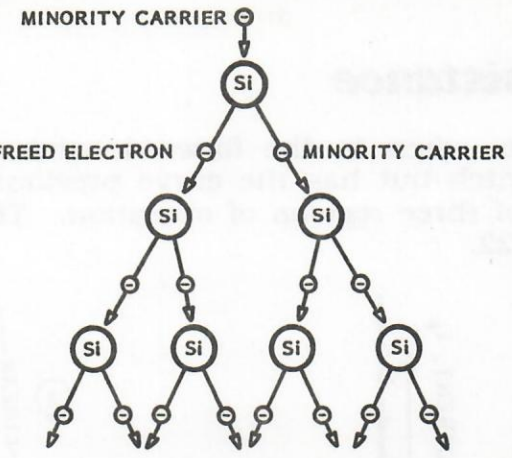


Figure 20 - Avalanche effect.

Peak Inverse Voltage

Avalanche occurs only when the reverse voltage reaches or exceeds a critical value called the PEAK INVERSE VOLTAGE, abbreviated piv. It is also called the PEAK REVERSE VOLTAGE, prv, or the MAXIMUM REVERSE VOLTAGE, mrv.

The reverse characteristic curve is combined with the forward characteristic curve as shown in Figure 21. Since the forward and reverse currents flow in opposite directions and are caused by opposite polarity voltages, they are presented in opposite quadrants of the graph, I and III.

The diode whose characteristics are shown in Figure 21 has a rated maximum forward current of 1 ampere and a piv rating of 40 volts. Note that at 45 volts piv, avalanche is just starting. If the diode is allowed to go into full avalanche, the diode will overheat and burn out, just as it will burn out if the maximum forward current rating is exceeded.

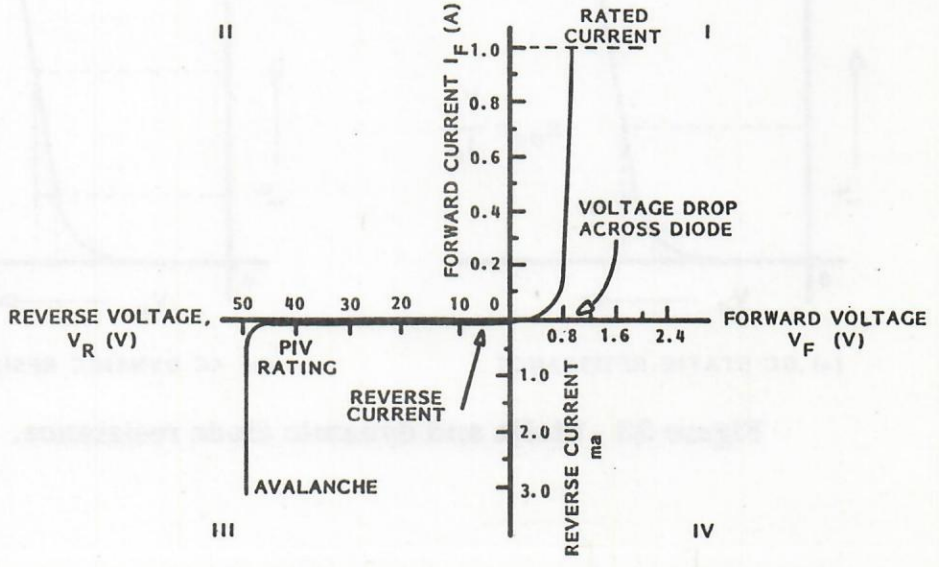


Figure 21 - Silicon diode forward and reverse characteristics.

Diode Resistance

The diode, when in the forward conducting range, is not an "ideal" switch but has the curve previously shown and actually consists of three regions of operation. These regions are shown in Figure 22.

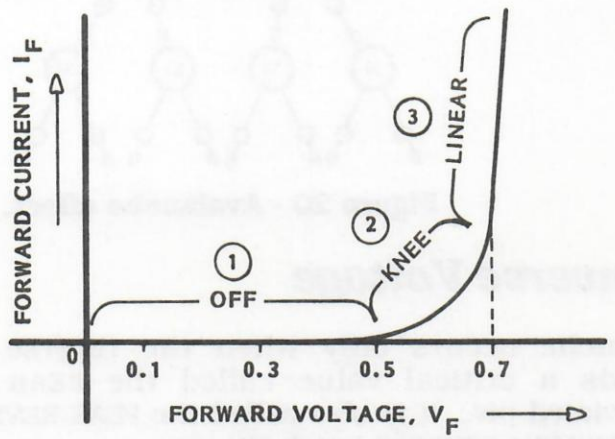
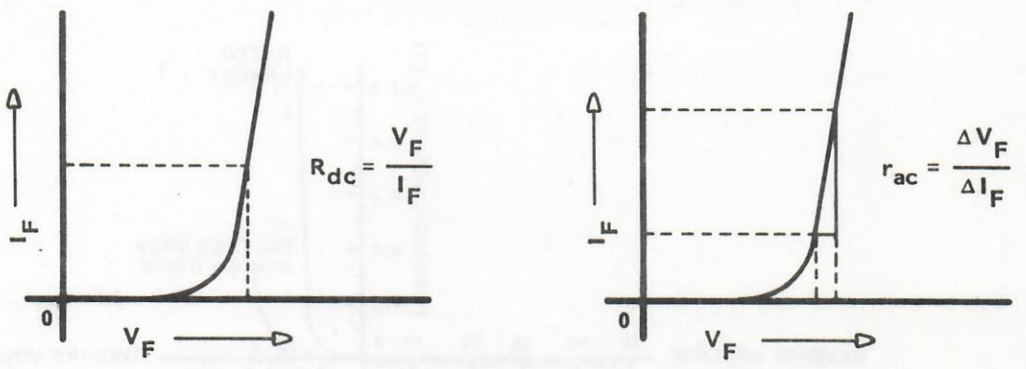


Figure 22 - Areas of operation in the diode's forward quadrant.

When the applied forward voltage is low (well below the barrier potential), the diode is OFF. The diode then begins to conduct in the KNEE area, region 2, and the rate of increase in IF is "rounded" or non-linear. In region 3, the curve becomes linear, like a resistor. We can define two resistances at a typical point in the linear region as shown in Figure 23(a) and (b). These are the STATIC DC resistance and the DYNAMIC DC resistance.



(a) DC STATIC RESISTANCE (b) AC DYNAMIC RESISTANCE

Figure 23 - Static and dynamic diode resistance.

The dc resistance in any region of the curve of Figure 23(a) is equal to the dc voltage divided by the dc current. Thus Rdc is expressed as:

$$Rdc = V_F / I_F$$

The ac resistance in the linear region, also called the BULK RESISTANCE can be determined as shown in Figure 23(b) and is expressed as:

$$rac = \Delta V / \Delta I$$

To enable you to determine the ac resistance (bulk resistance) of a diode, the manufacturer's data sheet will indicate the forward current, I_F, for a forward voltage, V_F, of 1 volt. In the case of a silicon diode, 0.7 volts is used to overcome the barrier potential and the balance of the voltage, 0.3 volts forward biases the diode and causes a current flow that is determined by the bulk resistance of the PN junction. If the data sheet indicates a current of 100 mA for an applied voltage of 1 volt, we can determine the ac resistance from:

$$rac = (1 - 0.7) / (0.1) = 0.3 / 0.1$$

$$rac = 3 \text{ ohms}$$

Diode Junction Resistance

The resistance in the knee or non-linear region of the diode changes with the applied voltage and subsequent current. As the current increases, the slope gets steeper and the resistance is less. The resistance and current in this area are "inversely" related; resistance is lowered as the current is increased. The resistance in the knee area is important because it controls the "valve" action in the PN junction in the transistor to be discussed later. For the diode, the resistance in the knee area is referred to as the DIODE JUNCTION RESISTANCE, rj.

When operated at the knee of the curve, the diode, at room temperature has a junction resistance, rj, that is approximated using the following equation that has been derived mathematically.

Diode Junction Resistance, rj = 25/ I

where I is the dc diode current in milliamperes. Given a diode current of 1.25 mA, the junction resistance is:

rj = 25 / I = 25 / 1.25

rj = 20 ohms

When the forward biased diode current is reduced, the junction resistance increases. Given a lower forward current of 0.2 mA, the junction resistance increases to:

rj = 25 / I = 25 / 0.2

rj = 125 ohms

Reverse Recovery Time (trr)

A major application for diodes is RECTIFICATION, that is changing ac to dc. The rectifier diode circuits can operate at power line frequencies and carry high currents to generate dc power or the rectifier diode circuits can be used for low voltage radio frequency signals at low current and power levels in radio receiver detector circuits. Different types of diodes must be used for each circuit as power diodes cannot operate properly at high frequencies and diodes designed for high frequency operation cannot handle high currents.

The highest frequency at which a diode will still act as a unidirectional device is determined by its REVERSE RECOVERY TIME, trr. When a diode is forward biased, electrons from the N-type material cross the junction to combine with the holes in the P-type material. These electrons in the P-type material are now MINORITY CARRIERS. When the diode is then reverse biased, the many electrons that crossed into the P-type region to become minority carriers, instantly flow back to the N region causing a momentary surge of high reverse current before dropping to the normal small reverse leakage current. The effect of these "trapped" minority electrons on the square wave being rectified by the diode, is shown in Figure 24.

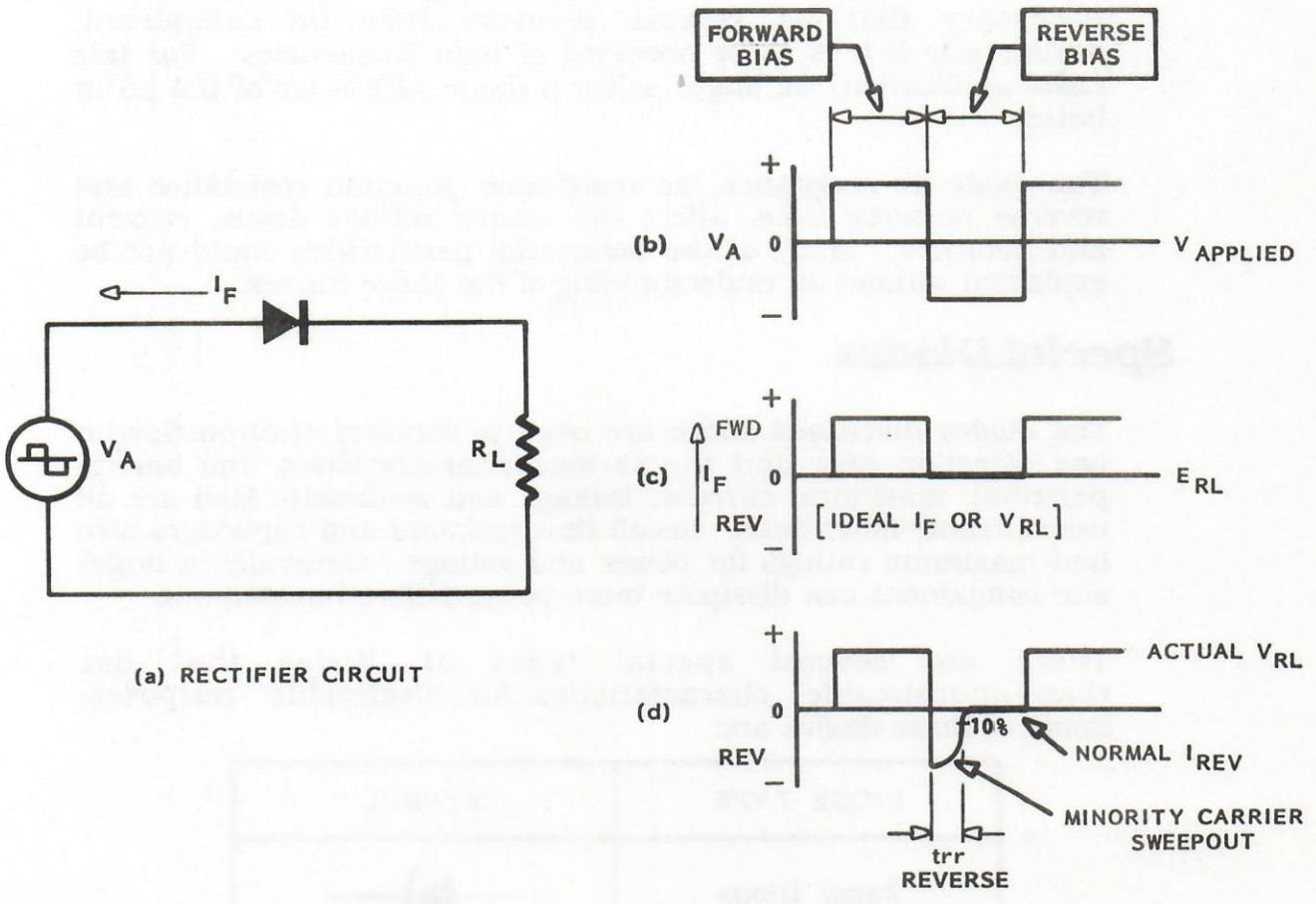


Figure 24 - Effect of trapped carriers on a rectified square wave.

Note the high reverse current spike in the output waveform (d) on the start of the reverse current flow, due to the trapped minority carriers. The removal of the trapped carriers is called *minority carrier sweepout*. The time period from the application of the reverse bias until the reverse current reduces to 10% of the peak reverse current is defined as the REVERSE RECOVERY TIME, trr. To see how trr affects rectification at different frequencies, consider the operation of a diode with a reverse recovery time of 4 µS. When rectifying a 60 Hz ac voltage for power circuits, the high reverse current lasts 4 µS out of a total time of 8,330 µS. This reverse time has little or no effect on the circuit operation.

If the input frequency to the same circuit is 125 kHz for radio applications, the operation changes drastically. A 125 kHz signal has a period of 8 µS and a half cycle has a duration of 4 µS. Current will flow in the circuit of Figure 24(a) for the full 4 uS of forward bias and the carrier sweepout will last 4 µS during the reverse bias period resulting in both halves of the cycle appearing across the load resistor, RL. In effect, there has been no diode rectification.

When a diode is to be selected for a given application, it is necessary that its reverse recovery time be considered, particularly if it is to be operated at high frequencies. For this radio application, we might select a diode with a trr of 0.4 μS or better.

The diode dc resistance, ac resistance, junction resistance and reverse recovery time, affect the circuit voltage drops, current and behavior. Many of the behavorial pecularities could not be explained without an understanding of the above causes.

Special Diodes

The diodes discussed above are used to conduct electron flow in one direction only and the various characteristics, the barrier potential, maximum current, leakage and avalanche (piv) are all undesireable limitations. Recall that resistors and capacitors also had maximum ratings for power and voltage. Generally, a larger size component can dissipate more power before burning out.

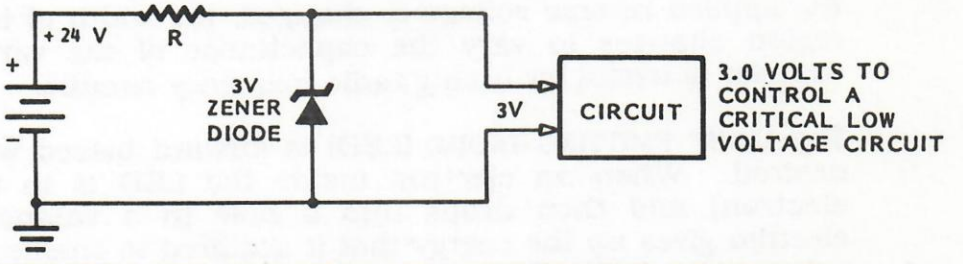
There are several special types of diodes that use these"undesireable" characteristics for "desireable" purposes. Some of these diodes are:

DIODE TYPE	SYMBOL
Zener Diode	
Varactor Diode	
Light Emitting Diode	

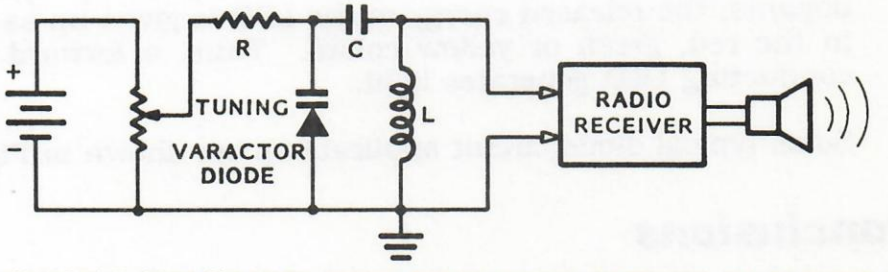
The ZENER DIODE is always used in the reverse biased avalanche mode. It is designed with the donor impurities evenly distributed across the PN junction so that a "controlled" reverse breakdown occurs at a specifically designed voltage called the ZENER VOLTAGE.

Thus a Zener diode provides us with specific fixed value voltage drop. Zener diodes are available with voltage drops from 1.5 to 200 volts.

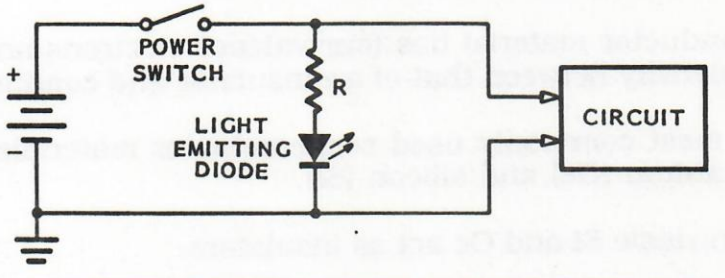
The VARACTOR DIODE is also always operated in the reverse direction. Here, the depletion region is used to advantage. The depletion region is an insulator and acts as a dielectric to separate



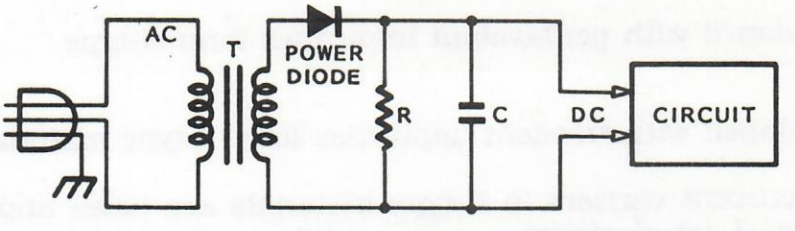
(a) ZENER DIODE REGULATOR PROVIDES FIXED LOWER REQUIRED DC VOLTAGE



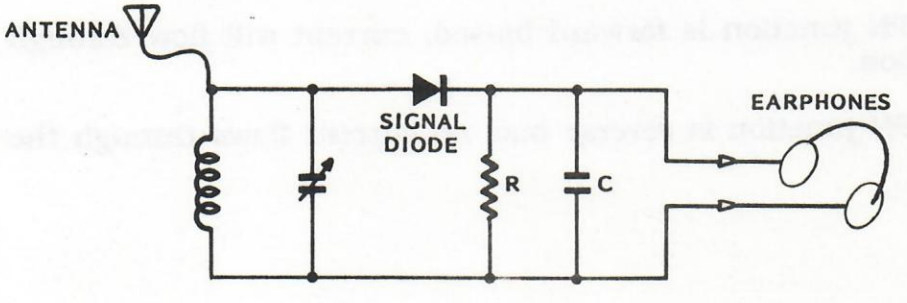
(b) VARACTOR VARIABLE CAPACITANCE DIODE TUNES RADIO RECEIVER TO DESIRED STATION



(c) LIGHT EMITTING DIODE INDICATES WHEN THE POWER IS ON



(d) RECTIFIER POWER DIODE CONVERTS AC TO DC



(e) SIGNAL DIODE DETECTS RADIO SIGNAL

Figure 25 - Typical diode circuit applications.

the positive and negative charges, thus acting as a CAPACITOR. As the applied reverse voltage is changed, the width of the depletion region changes to vary the capacitance of the varactor. The varactor is useful for tuning radio frequency circuits.

The LIGHT EMITTING DIODE (LED) is forward biased when light is desired. When an electron inside the LED is in flow (a free electron) and then drops into a hole in a valance ring, the electron gives up the energy that it acquired to enable it to leave a valence ring in the first place. This energy is released in the form of heat, light or other "radiation." By the proper choice of dopants, the released energy in the LED is given up as visible light in the red, green or yellow colors. Thus, a forward biased and conducting LED generates light.

Some typical diode circuit applications are shown in Figure 25.

Conclusions

We have learned from this information sheet that:

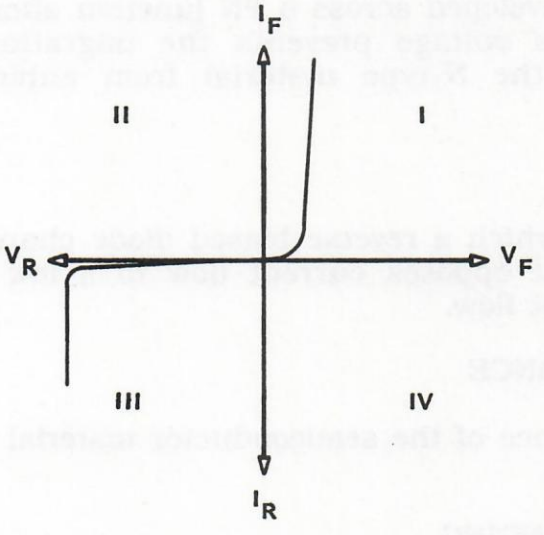
1. A semiconductor material has four valence electrons and has a resistivity between that of an insulator and conductor.
2. The two most commonly used semiconductor materials are germanium (Ge) and silicon (Si).
3. Pure or intrinsic Si and Ge act as insulators.
4. Impurities, called dopants, are added to intrinsic Ge and Si.
5. Ge or Si doped with pentavalant impurities form N-type material.
6. Ge or Si doped with trivalent impurities form P-type material.
7. Majority current carriers in P-type materials are holes and in N-type material are electrons.
8. When a PN junction is created, a barrier potential appears.
9. When a PN junction is forward biased, current will flow through the junction.
10. When a PN junction is reverse bias no current flows through the junction.

11. If the intrinsic material used to form the PN junction has not been totally purified a leakage current will flow when the junction is reversed biased.

12. A Ge PN junction will exhibit more leakage than an Si type.

13. The symbol for a PN junction, also called a diode, is:

14. Diode characteristics are shown on a four quadrant graph as below.



15. When the piv of a diode is increased beyond the rated value, avalanche occurs and the diode will burn out.

16. The bulk or ac resistance of a diode is calculated from:

rbulk = (1V - V barrier) / I diode

17. The diode junction resistance when biased close to the knee of the forward curve is determined from:

rj = 25 / I in mA

Key Terms

1. ACCEPTOR IMPURITY

   A dopant with too few valence electrons to complete the bonding structure in a semiconductor material.

2. AVALANCHE

   A rapid rise of current flow in a reverse biased diode when the reverse voltage reaches a critical high value.

3. BARRIER POTENTIAL

   The voltage developed across a PN junction after the junction is formed. This voltage prevents the migration of most free electrons in the N-type material from entering the P-type material.

4. BREAKDOWN

   The point at which a reverse biased diode changes from a high resistance that opposes current flow to a low resistance that permits current flow.

5. BULK RESISTANCE

   The ac resistance of the semiconductor material (Si, Ge) used to form the diode.

6. COVALENT BONDING

   A link between atoms formed by sharing valence electrons.

7. CRYSTAL STRUCTURE

   A solid material in which the atoms are arranged in a regular geometric pattern. A crystal structure is formed by Si and Ge when in a pure state (intrinsic).

8. DEPLETION REGION

   The area on both sides of the PN junction of a reverse biased semiconductor diode from which all current carriers are removed by the reverse bias. An area in which all current carriers are removed, acts as an insulator.

9. DONOR ATOM

A pentavalent impurity atom that contributes one extra electron to the covalent bonding structure. The extra electron is free from the crystal structure to conduct.

10. DOPING

The process of adding controlled amounts of impurities to intrinsic Si or Ge to form N or P-type materials.

11. FORWARD BIAS

A voltage applied to a PN junction in such a polarity as to cancel the barrier potential and permit a high current flow. The applied voltage polarity is plus to the P-type and minus to the N-type materials.

12. FORWARD CURRENT (I_F)

The current that flows through a forward biased PN junction.

13. FORWARD VOLTAGE DROP (V_F)

The low voltage drop across a forward biased semiconductor diode. The forward voltage will be 0.7 volts for Si and 0.3 volts for Ge.

14. GERMANIUM

Germanium, Ge, is a semiconductor material used for diodes and transistors.

15. HOLE FLOW

Current flow in a P-type semiconductor material where electrons move into holes when a voltage is applied. The apparent movement of holes is toward the negative terminal of the source while the movement of electrons it toward the positive terminal of the source.

16. IMPURITY

A material with a 3 electron valence ring (trivalent) or 5 electron valence ring (pentavalent) added to intrinsic Ge or Si to create P or N-type materials.

17. JUNCTION

The area in a PN junction where the P material changes to N material.

18. JUNCTION RESISTANCE

The resistance exhibited by the junction for a given forward current. The junction resistance is approximated from:

$$r_j = 25 / I_F \text{ in mA}$$

19. KNEE

The point on graphic plot when an abrupt change occurs. In the diode forward characteristic curve the knee occurs at the barrier potential. In the reverse characteristics the knee occurs at the avalanche or breakdown potential called the piv.

20. LEAKAGE

An unwanted flow of electrons when a diode is reverse biased.

21. LIGHT EMITTING DIODE (LED)

A diode that emits light when forward biased.

22. MAJORITY CARRIERS

The main current carrier in a doped semiconductor material. These are electrons in the N-type material and holes in the P-type material.

23. MINORITY CARRIERS

Current carriers in a semiconductor material that are from impurities remaining after the intrinsic material has been purified. In N-type material the minority carriers are holes and in P-type they are electrons.

24. N-TYPE MATERIAL

Intrinsic semiconductor material that has been doped with a pentavalent impurity and so has free electrons available for conduction.

25. PEAK INVERSE VOLTAGE (piv)

The maximum voltage that a PN junction can withstand in the reverse direction without breaking down. Also known as the peak reverse voltage (prv).

26. PENTAVALENT IMPURITY

An impurity atom whose valence ring contains five electrons. Creates N-type material when added to intrinsic Si or Ge.

27. PN JUNCTION

A PN junction is another term for a diode.

28. P-TYPE MATERIAL

The intrinsic semiconductor material that has been doped with a trivalent impurity and so has holes in the covalent bond structure that accepts electrons.

29. REVERSE BIAS

A voltage applied to a PN junction in such a polarity as to reinforce the barrier potential and block current flow. The applied voltage polarity is plus to the N-type and minus to the P-type material.

30. REVERSE CURRENT FLOW (I_R)

The leakage current that flows when a diode is reverse biased (I_R). The leakage current is due to impurities remaining in the intrinsic Si or Ge that provide electrons in the P-type and holes in the N-type materials.

31. SEMICONDUCTOR

A material with a resistivity between that of a conductor and an insulator. Semiconductors have four valence electrons whereas insulators have eight and conductors one valence electron.

32. SHARING BONDS

See Covalent Sharing Bonds.

33. SILICON

Silicon, Si, is a semiconductor material used for diodes andtransistors.

34. SOLID STATE DEVICES

Components made of semiconductor materials. Typical devices are diodes and transistors.

35. TRIVALENT IMPURITY

An impurity atom whose valence ring contains three electrons. Creates P-type material when added to intrinsic Si or Ge.

36. VACUUM TUBE

An electron operated device housed in a vacuum. The housing is normally made of glass or metal.

37. VALENCE RING

The ring formed by the outermost electrons in an atom.

38. VARACTOR DIODE

A diode that acts as a variable capacitance.

39. ZENER DIODE

A diode that can be wired into a circuit so as to provide a constant voltage drop.

Assignment

Answer the following multiple choice questions.

1. The valence ring of an atom contains: _____

   a) a maximum of 12 electrons.
   b) a maximum of 8 protons.
   c) electrons only.
   d) a mix of electrons and protons.

2. A material whose atoms contain valence rings with eight electrons, will act as a (an): _____

   a) semiconductor.
   b) insulator.
   c) conductor.
   d) superconductor.

3. One of the more frequently used semiconductor materials is: _____

   a) silicon (Si).
   b) antimony (Sb).
   c) aluminum (Al).
   d) copper (Cu).

4. A semiconductor material is one whose valence ring contains: _____

   a) 4 electrons.
   b) 1 electron.
   c) 8 electrons.
   d) 16 electrons.

5. Silicon, in its intrinsic state, behaves like a (an): _____

   a) good conductor.
   b) semiconductor.
   c) superconductor.
   d) insulator.

6. Intrinsic silicon contains: _____

   a) many impurity atoms.
   b) virtually no impurity atoms.
   c) half silicon atoms and half antimony atoms.
   d) none of the above.

7. Pure silicon is doped with a trivalent material such as boron or gallium in order to create: _____

   a) an N-type material.
   b) intrinsic silicon.
   c) a dopant.
   d) a P-type material.

8. N-type silicon has a: _____

a) neutral charge.
b) positive charge.
c) negative charge.
d) b or c but never a.

9. P-type germanium has a: _____

a) neutral charge.
b) positive charge.
c) negative charge.
d) b or c but never a.

10. When silicon is doped with a pentavalent impurity, the crystalline structure contains: _____

a) holes.
b) extra electrons.
c) a positive charge.
d) a negative charge.

11. In N-type material the majority carriers are _____ and the minority carriers are _____. _____

a) holes; electrons
b) holes; indium
c) electrons; boron
d) electrons; holes

12. The majority current carriers in P-type silicon are_____ and the minority carriers are _____.

a) holes; electrons
b) electrons; electrons
c) holes; holes
d) electrons; holes

13. When the PN junction is formed: _____

a) electrons move from the N to P sections.
b) a barrier potential is developed.
c) the N-type material becomes positively charged.
d) all of the above.

14. When a PN junction is forward biased the: _____

a) junction has low oppostion to current flow.
b) current flow is opposed by the bulk resistance
c) barrier potential is cancelled.
d) all of the above.

15. When a PN junction is reverse biased: _____

a) a depletion region forms at the junction.
b) the barrier potential is cancelled.
c) the diode resistance is very low.
d) all of the above.

Figure 26 above refers to questions 16 to 18.

16. In the diode symbol shown in Figure 26, terminal (A) is the:_____

a) anode.
b) cathode.
c) cathode only if the PN junction is silicon.
d) cathode only if the PN junction is germanium.

17. In the diode symbol shown in Figure 26, side (A) is_____ and side (B) is_____ material. _____

a) N-type; P-type.
b) P-type; N-type.
c) silicon; germanium.
d) germanium; silicon.

18. The direction of _____flow through the diode shown in Figure 26 is from _____. _____

a) electron; (A) to (B).
b) hole; (B) to (A).
c) electron (B) to (A).
d) none of the above.

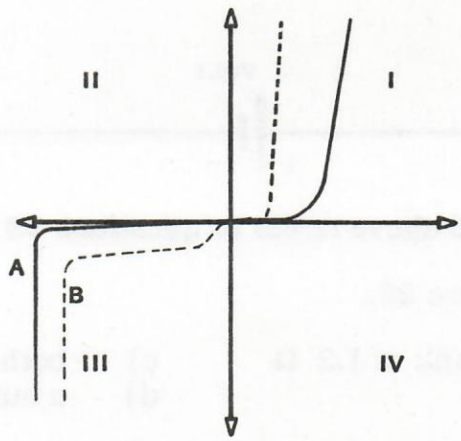


Figure 27 above refers to questions 19 to 22.

19. The four quadrant graph in Figure 27 shows the_____ characteristics in quadrant ____. _____

a) Reverse; I
b) Forward; III
c) Reverse; II
d) Forward; I

20. In the four quadrant graph of Figure 27, the dotted line is the characteristic of a _____diode and the solid line is the characteristic of a _____diode. _____

a) silicon; indium. c) silicon; germanium
b) germanium; silicon d) germanium; boron

21. In the four quadrant graph of Figure 27, the area marked A in quadrant III represents: _____

a) the forward current. c) avalanche point.
b) the piv. d) both b and c.

22. In the four quadrant graph of Figure 27, the area marked B in quadrant III represents: _____

a) Si and Ge leakage current. c) avalanche.
b) Si and Ge barrier potential. d) none of the above.

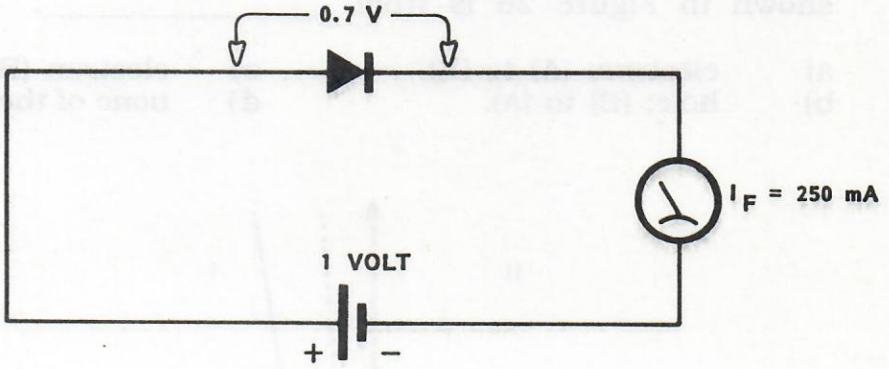


Figure 28 above refers to questions 23 and 24.

23. The diode in Figure 28: _____

a) has an r bulk of 1.2 Ω. c) both a and b.
b) is silicon. d) a but not b.

24. When the diode of Figure 28 is forward biased by a voltage of 0.55 volts and a diode current of 0.75 mA flows the junction resistance is approximately: _____

a) 0.55 ohms. c) 1.53 ohms.
b) 33 ohms. d) none of the above.

Rectifier Circuits

Info Sheet 2

Objectives

When you finish this information sheet you will be able to:

1. Draw the circuit of a half-wave rectifier and explain its operation.
2. Draw the circuit of a full-wave rectifier and explain its operation.
3. Draw the circuit of a bridge rectifier and explain its operation.
4. Calculate the expected peak and average output voltages for each type of rectifier circuit.
5. Draw the output waveforms and specify the ripple frequencies for each type of rectifier circuit.
6. Calculate the peak inverse voltage the diodes are subjected to in each type of rectifier circuit.

Discussion

With few exceptions, electronic equipment requires a pure or constant value dc voltage source for normal operation while the power delivered to homes and factories at the electrical outlet is ac. Either one must use batteries (dc) to power the electronic equipment or a method must be used to convert the available ac to a pure dc of the proper voltage value. The circuit used to perform this function is called a POWER SUPPLY and the circuit requires the use of diodes.

The power supply can be divided into three major sections as shown in Figure 1. The first block is the power transformer. Its function is to increase (step-up) or decrease (step-down) the 117 volt power line to the required voltage.

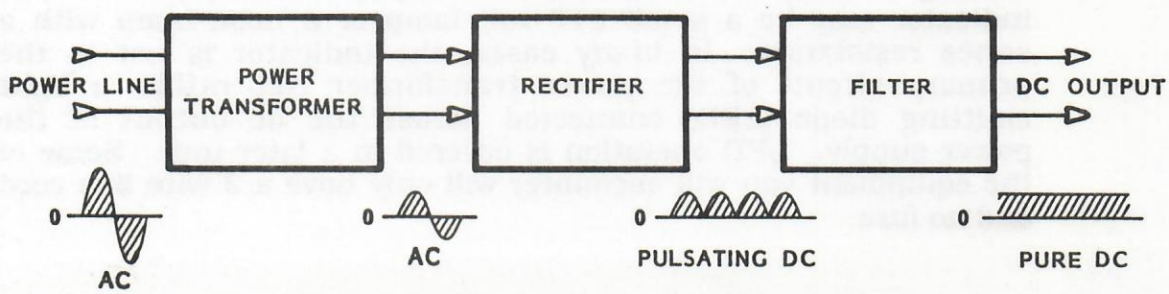


Figure 1 - Block diagram of a basic power supply.

The second block in Figure 1 contains the RECTIFIER CIRCUIT. The function of the rectifier circuit, which consists of diodes, is to change the ac to pulsating dc.

The third block in Figure 1 is the FILTER CIRCUIT which is used to remove all pulsations and variations from the output voltage thus providing a pure, steady dc. Filter circuits are covered in Information Sheet 3. In many power supplies, another block follows the filter, called a REGULATOR, which provides an accurately controlled dc voltage.

Power Transformer Primary Circuit

All power supplies that use power transformers require that the primary of the transformer be properly connected to the power line. The basic power transformer primary wiring is shown in Figure 2.

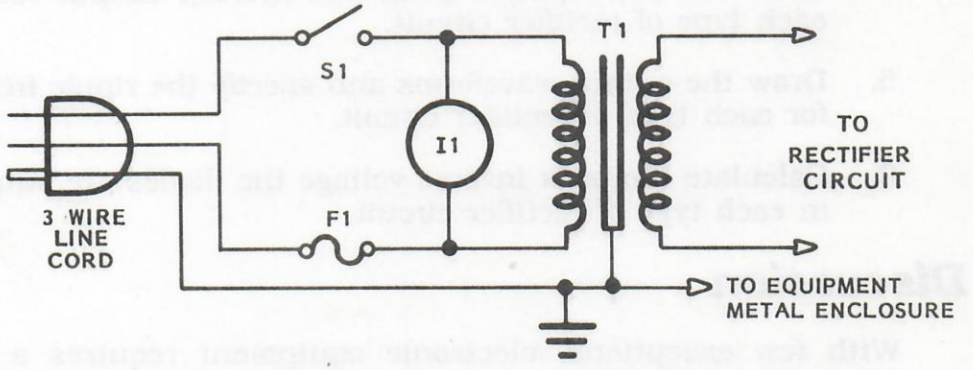


Figure 2 - Power transformer primary wiring circuit.

A three wire line cord and plug is preferred so that the metal enclosure of the equipment, if any, can be directly grounded as a safety precaution. This concept was explained earlier in Unit G3, Experiment 6, External Test Equipment. Switch S1 controls the application of power to the transformer primary and is the On-Off switch. Fuse F1 protects the power transformer against current overloads. A short anywhere in the circuit connected to the secondary will raise the primary current causing the fuse or a circuit breaker to open before T1 overheats. An indicator lamp, I1, may be used to indicate when the equipment is powered. The indicator may be a small 117 volt lamp or a neon lamp with a series resistance. In many cases, the indicator is not in the primary circuit of the power transformer but rather a light emitting diode (LED) connected across the dc output of the power supply. LED operation is covered in a later unit. Some of the equipment you will encounter will only have a 2 wire line cord and no fuse.

Half-Wave Rectification

The basic HALF-WAVE RECTIFIER circuit is shown in Figure 3. Note that the wiring of the primary of T1 to the line cord is not shown but is understood to be present.

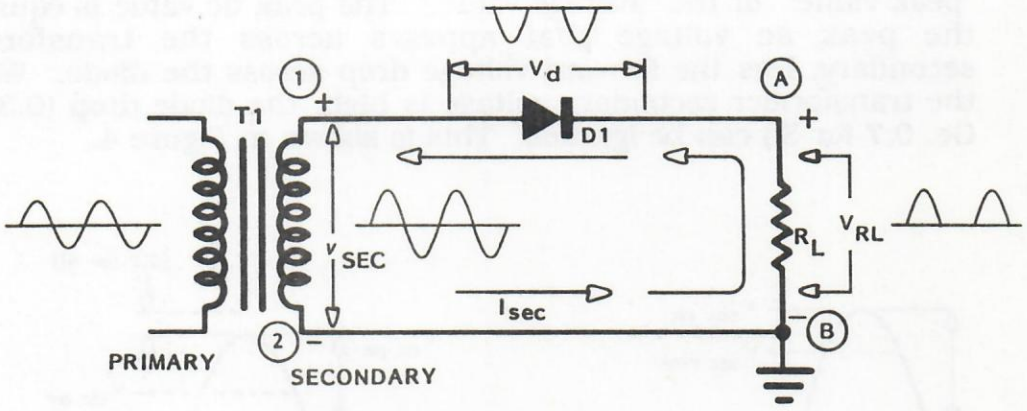


Figure 3 - Half-wave rectifier circuit and waveforms.

The power transformer, T1, changes the line voltage to the desired value. When terminal 1 of the T1 secondary is positive with respect to terminal 2, the diode, D1, is forward biased. Electrons leave the negative end of the transformer secondary, flow through the load, RL, through the diode and return to the positive end of the secondary winding, terminal 2. As the positive half of the ac cycle rises from zero to the positive peak and back to zero, the output voltage across the load resistance, RL, follows to reproduce the positive half cycle, and the voltage drop across the diode is very low.

On the second half of the ac cycle appearing across the T1 secondary, the polarity reverses and terminal 1 is negative with respect to terminal 2. The diode is now reverse biased, no current flows and there is no voltage drop across RL. The resulting waveform for two cycles of input is shown. The positive half pulses appear across RL and the negative half pulses appear across D1. Note, in Figure 3, that one end of RL (B) is connected to ground; the voltage at terminal (A) is always positive with respect to ground.

If we wish the voltage at (A) to be negative with respect to ground, it is necessary to reverse the diode polarity. This will allow conduction on the negative half cycles thus reversing the direction of current flow in the secondary circuit.

DC Output Voltage

The pulsating dc output voltage of the half-wave rectifier appears across RL as shown in Figure 3. Measuring this output voltage can be done in several ways because, while it is dc, it is not constant in value. The measurement of the output voltage can be by the "peak value" or the "average value." The peak dc value is equal to the peak ac voltage that appears across the transformer secondary, less the forward voltage drop across the diode. When the transformer secondary voltage is high, the diode drop (0.3 for Ge, 0.7 for Si) can be ignored. This is shown in Figure 4.

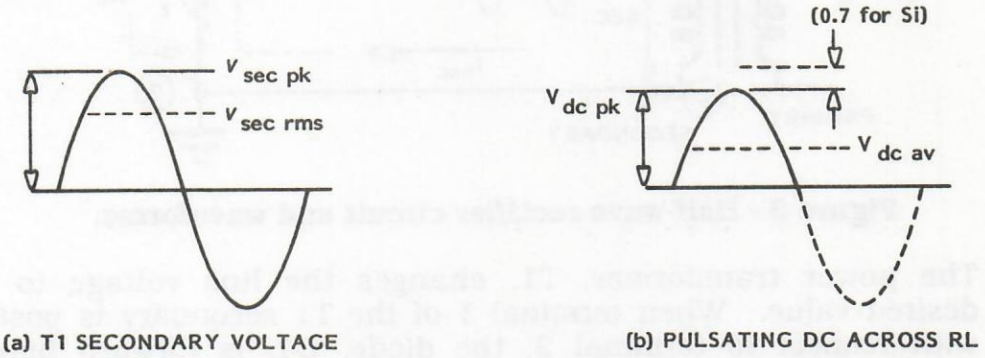


Figure 4 - Rectifier input and output waveforms.

When the secondary rms voltage is known, and it can be measured using an ac voltmeter, the peak dc output, after rectification, can be determined from:

$$V_{dc\ peak} = [(v\ sec\ rms)\ (1.414)] - (V_{diode}) \qquad (1)$$

The "Vdc peak voltage," after rectification, is there for only a brief instant and thus cannot be a true measure of power capability. The *AVERAGE* dc voltage (Vdc av in Figure 4(b)) across RL is a better indicator of the rectifier output voltage capability. The average dc voltage is determined by the peak amplitude of the rectified pulses. The greater the peak, the greater the average dc across RL.

Because the voltage waveform across RL is a half sine wave, it is possible to calculate the average dc based on the average voltage of a complete sine wave and then divide the result by two. It was shown earlier in Unit G1, Information Sheet 2, Alternating Current and Voltage, that the average voltage for a complete sine wave is equal to:

$$v_{ac\ av} = (v\ pk)\ (0.637)$$

Dividing by two for half-wave rectification, we have:

$$\text{Vdc av} = [(v \text{ pk}) (0.637)] / 2$$

Thus, for half-wave rectification:

$$\text{Vdc av} = (v \text{ pk})(0.318) \qquad (2)$$

Because transformer primary and secondary voltages are always given in rms values by the manufacturer, equation (2) is normally given as:

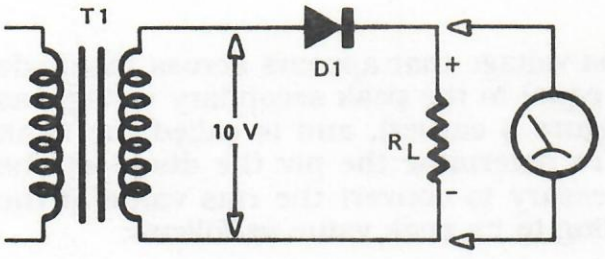
$$\text{Vdc av} = [(v \text{ sec rms}) (1.414) (0.637)] / 2$$

which simplifies to:

$$\text{Vdc av} = (v \text{ sec rms}) (0.45) \qquad (3)$$

Equations (2) and (3) both disregard the rectifier diode voltage drop which is usually small compared to v sec rms.

Given a transformer with a secondary voltage of 10 volts as shown in Figure 5, Vdc av is calculated as illustrated.



Vdc av = (v sec rms)(0.45)
= (10) (0.45)
Vdc av = 4.5 V

Figure 5 - The dc output calculation for a half-wave rectifier.

When a filter capacitor is added, the output dc voltage will increase and rise closer to the peak voltage. This is discussed in a later information sheet on filter circuits.

Peak Inverse Voltage

The instantaneous voltage distribution in the half-wave rectifier circuit is shown in Figure 6.

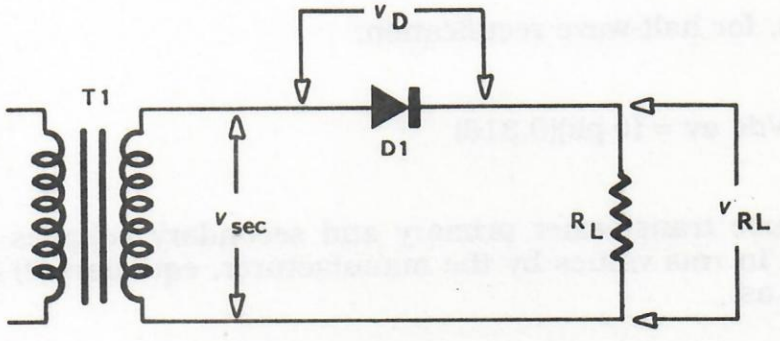


Figure 6 - Instantaneous voltage distribution in the half-wave rectifier circuit.

Based on Kirchhoff's voltage law, the instantaneous voltage distribution in the circuit of Figure 6 may be expressed as:

$$\upsilon \text{ sec} = \upsilon \text{d} + \upsilon \text{RL} \qquad (4)$$

When the diode is forward biased υRL equals υsec less the small diode drop (0.3 or 0.7 volts). When the diode is reverse biased, the diode is an open circuit and υRL drops to zero volts. Thus, in the reverse biased state, as indicated by equation (4), it can be seen that:

$$\upsilon \text{ sec} = \upsilon \text{d} + 0$$

$$\upsilon \text{ sec} = \upsilon \text{d}$$

The maximum instantaneous voltage that appears across the diode when it is reverse biased is equal to the peak secondary voltage, as shown in Figure 6 (and Figure 3 earlier), and is called the PEAK INVERSE VOLTAGE or piv. To determine the piv the diode will be subjected to, it is only necessary to convert the rms value of the transformer secondary winding to its peak value as follows:

$$\text{Rectifier Reverse Voltage: piv} = \upsilon \text{ sec rms } (1.414) \qquad (5)$$

For the circuit of Figure 5, with the 10 volt secondary, the peak inverse voltage across the diode is:

$$\text{piv} = 10\ (1.414) = 14.4 \text{ volts}$$

This means that, when reverse biased, the diode has 14.14 volts across it trying to force a current flow through the diode in the reverse direction. If the diode cannot withstand this reverse voltage (piv), it will "break down" and conduct in both directions. For this reason, the piv rating of a diode, given in the diode specification sheets, should not be exceeded.

Half-Wave Ripple Frequency

Examination of the output wave form across RL in Figure 3 shows it to be dc, that is, the output voltage never reverses polarity. The voltage, however, is not a steady or constant dc. It is a combination of dc and ac and is called a PULSATING dc. The output pulsations have a definite repetition rate or frequency. Since the diode conducts once during each input cycle, the pulsating frequency of the output is equal to the input frequency. Thus, for a 60 Hz power line frequency, the output pulses will appear at a 60 Hz rate. The pulses in the output are called RIPPLE and thus, for a half-wave (hw) rectifier the ripple frequency equals the line frequency and is shown as in equation (6).

Half-Wave Rectification : f ripple (hw) = f line (6)

Full-Wave Rectification

The half-wave rectifier circuit uses one half of the ac input which is delivered to the load while the other half of the input cycle is not used.

The FULL-WAVE rectifier circuit uses both halves of the ac input cycle to produce the dc output. The full-wave rectifier and the circuit waveforms are shown in Figure 7.

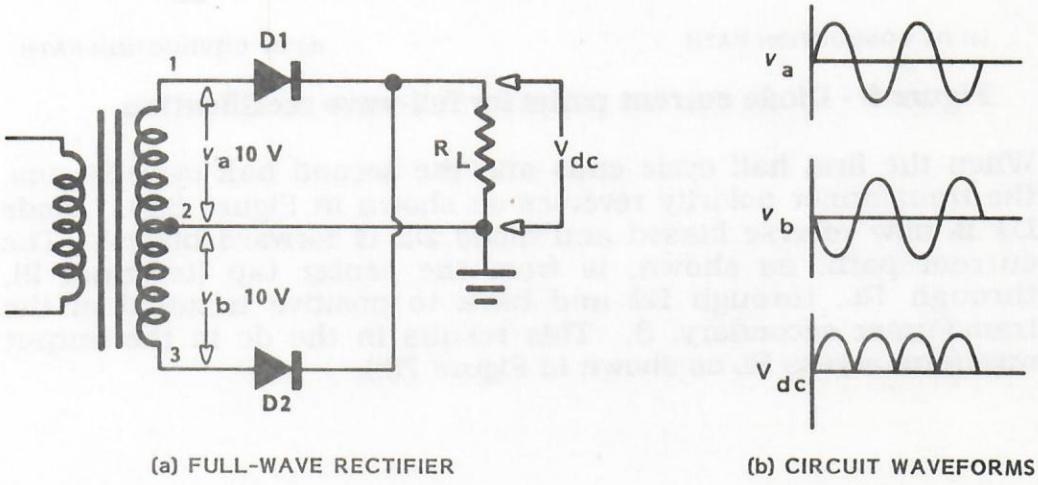


Figure 7 - Full-wave rectifier circuit and waveforms.

The circuit of Figure 7(a), if examined closely, can be seen to be a combination of two half-wave rectifiers each conducting on a alternate half cycles. The transformer secondary winding is double that used for the half-wave, providing 20 volts. Note that a "center tap" (CT) connection is used. The transformer is said to have a *center-tapped secondary.*

Two voltages are developed across the secondary, *v*a from terminals 1 to 2 and *v*b from terminals 2 to 3. The two voltages, taken from terminals 1 and 3 are 180 degrees out of phase with each other as shown in Figure 7(b). Terminal 2 of the secondary is the common or reference point and is normally at ground potential.

The rectifying action on the first half cycle is shown in Figure 8(a). Diode D1 is forward biased by voltage *v* a. Diode D2 is reverse biased by voltage *v* b. With diode D1 conducting, the electron flow is from terminal 2 to RL, through RL, through D1, back to terminal 1 of T1. The waveshape of the dc output voltage, Vdc, is that of the input voltage for one half cycle. During this entire half cycle, diode D2 is reverse biased and does not conduct.

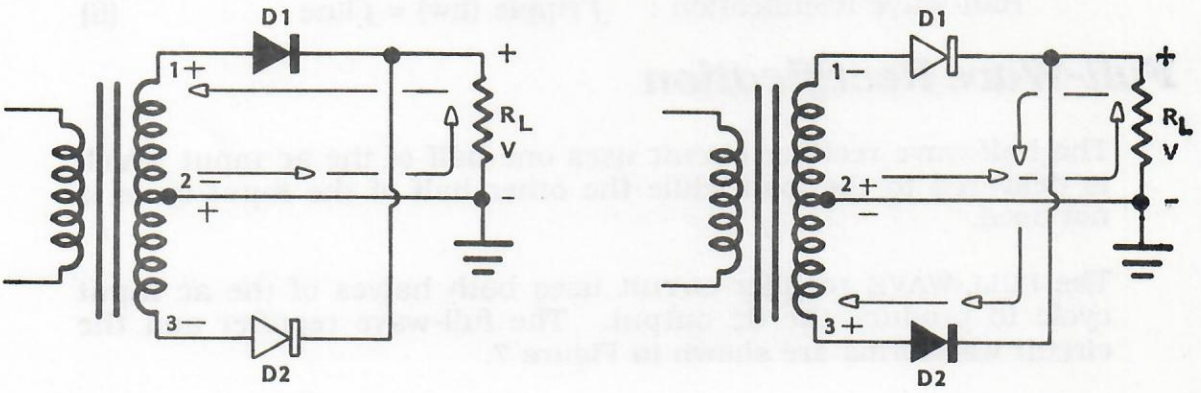


Figure 8 - Diode current paths for full-wave rectification.

When the first half cycle ends and the second half cycle begins, the transformer polarity reverses as shown in Figure 8(b). Diode D1 is now reverse biased and diode D2 is forward biased. The current path, as shown, is from the center tap (terminal 2), through RL, through D2 and back to positive terminal of the transformer secondary, 3. This results in the dc in the output waveform across RL as shown in Figure 7(b).

Full-Wave DC Output Voltage

The average value of the dc output voltage from a full-wave rectifier is twice that from the half-wave circuit. Because the output waveform is a sine wave but with both halves of the output wave of the same polarity, the average voltage is the full 0.637 of the peak voltage. Thus, for full-wave operation:

$$V_{dc\ av\ (fw)} = v_{pk}\ (0.637) \qquad (7)$$

In terms of the rms voltage, of the transformer secondary, Vdc av, may be expressed as:

$$V_{dc\ av\ (fw)} = v_{rms}\ (0.9) \qquad (8)$$

Given the full-wave rectifier circuit of Figure 8 with a specified 20 volts rms center tapped transformer secondary (10-0-10), the average dc output voltage will be 9 volts. While the total secondary voltage is 20 volts, each diode sees only 10 volts, one half of the secondary. Because of this, when calculating the average dc output, only one half of the full secondary voltage is to be used. Modifying equation (8), we have:

$$V_{dc\ av} = [(v_{sec} / 2)]\ (0.9) \qquad (8b)$$

$$V_{dc\ av} = [(20 / 2)]\ (0.9) = 9 \text{ volts}$$

One of the differences between the full-wave rectifier and the half-wave rectifier is that full-wave requires a secondary winding that develops twice the voltage and is center-tapped. This means twice the number of turns on the secondary making the transformer larger and more costly. The full-wave rectifier is usually more advantageous because it requires less filtering. This is explained in the next information sheet, which describes how the filter reduces the level of pulsations or ripple to produce a constant level or "pure" dc voltage.

Full-Wave Rectifier PIV

In the full-wave rectifier circuit, the piv that appears across each diode, when it is in the non-conducting state, is equal to the peak voltage that appears across the *full* secondary winding. This is shown in Figure 9 where diode D2 is conducting.

Because D2 is conducting and D1 is reverse biased, the peak secondary voltage will appear across D1 with the polarity shown in Figure 9. With a full secondary of 20 volts rms, the piv will be:

$$piv = (v\ sec)\ (1.414)$$

$$piv = (20)\ (1.414)$$

$$piv = 28.28 \text{ volts}$$

The same peak inverse voltage will appear across D2 when it is reverse biased and D1 is conducting.

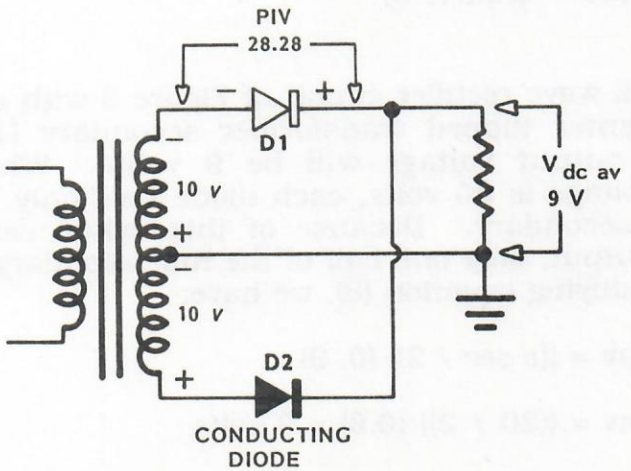


Figure 9 - Diode piv equals peak *v* secondary.

Full-Wave Ripple Frequency

When the output waveform of the full-wave rectifier is examined (Figure 7(b)), it can be seen to contain two pulses of voltage for each input cycle. The ripple frequency at the output of a full-wave rectifier is, therefore, equal to twice the line frequency or:

$$f \text{ ripple (fw)} = 2 \times f \text{ line} \qquad (9)$$

Given the normal line frequency of 60 Hz, the full-wave ripple frequency will then be 120 Hz. The higher ripple frequency of the full-wave is an advantage because the output more closely resembles pure dc and has a higher average voltage. Because of this, as will be shown later, the full-wave output is easier to filter than the output of the half-wave rectifier.

Bridge Rectification

In the half-wave rectifier circuit, the peak dc output voltage is equal to the peak ac input to the rectifier. In the full-wave circuit, to obtain the same peak dc output as in the half-wave circuit, *twice* the secondary ac voltage is required. It is possible, however to use a circuit that requires no more secondary ac voltage than the half-wave rectifier, does not require a center tap, produces the same dc output voltage and is also full-wave. The circuit is called a BRIDGE RECTIFIER and is shown in Figure 10. Note that it requires four diodes.

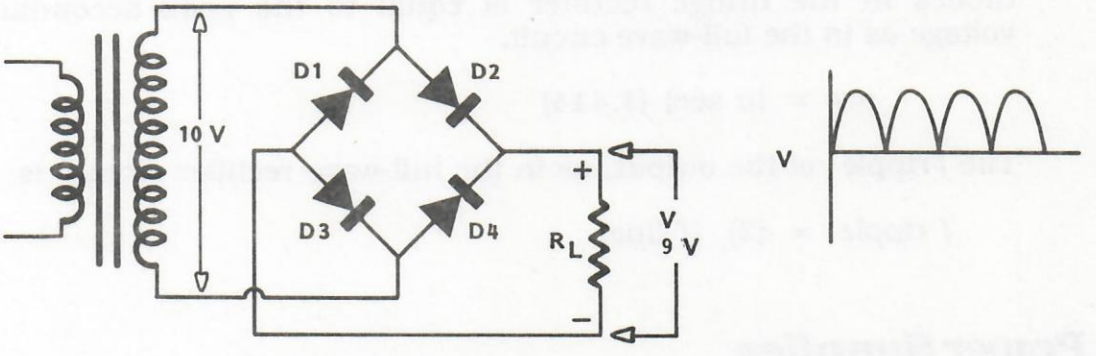
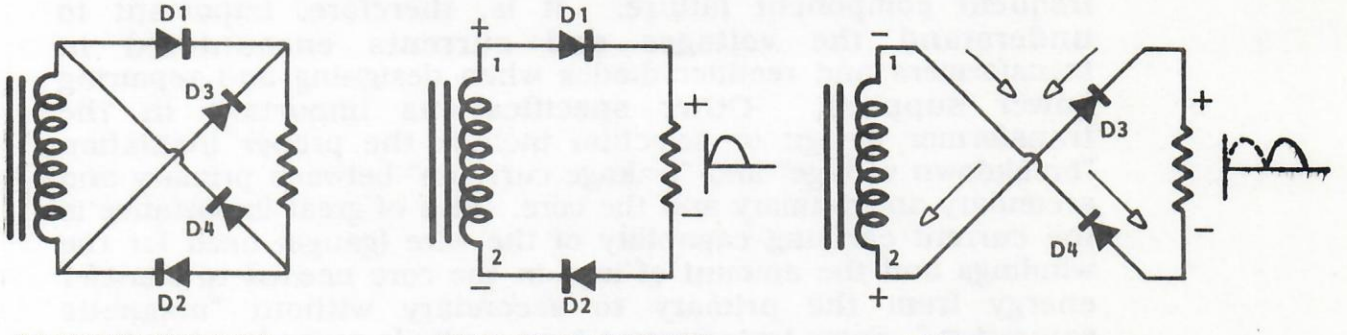


Figure 10 - Bridge rectifier circuit and output waveform.

For a 10 volt ac secondary, the output voltage will peak at 14.14 volts and produce an average dc of 9 volts. The method of drawing the bridge rectifier is changed in Figure 11(a) to show the circuit operation more clearly.



(a) BRIDGE RECTIFIER (b) D1-D2 CONDUCTION (c) D3-D4 CONDUCTION

Figure 11 - Bridge rectifier conduction paths.

In Figure 11(b), on the first half cycle, terminal 1 of the secondary is positive and terminal 2 is negative. Electrons leave the negative terminal, flow through D2, through RL and D1 to return to terminal 1, the positive end of the secondary. The half cycle of

the output waveform is shown across RL. Diodes D3 and D4 are not shown as they are reverse biased and not conducting.
On the second half of the input cycle, diodes D1 and D2 are reverse biased and so are not shown. Diodes D3 and D4 now conduct and, as illustrated, have switched RL to the opposite ends of the secondary to maintain the same output polarity.

For the bridge rectifier, the average dc output voltage is also determined from:

$$Vdc\ av = (v\ sec)\ (0.9)$$

The peak inverse voltage (piv) that appears across each of the four diodes in the bridge rectifier is equal to the peak secondary voltage as in the full-wave circuit.

$$piv = (v\ sec)\ (1.414)$$

The f ripple of the output, as in the full-wave rectifier circuit, is:

$$f\ ripple = (2)\ (f\ line)$$

Power Supplies

The power supplies for equipment such as computers, radio communications receivers and television receivers must provide all the dc voltages and currents to the various circuits. These power supplies, when delivering these often high currents, have to dissipate power internally and so "heat up" resulting in frequent component failure. It is, therefore, important to understand the voltages and currents encountered in transformers and rectifier diodes when designing and repairing power supplies. Other specifications important in the transformer design or selection include the proper insulation "breakdown voltage" and "leakage currents" between primary and secondary and primary and the core. Also of great importance is the current carrying capability of the wire (gauge) used for the windings and the amount of iron in the core needed to transfer energy from the primary to secondary without "magnetic saturation." Some transformers have multiple secondary windings when many different dc output voltages are required.

Conclusions

We have learned from this information sheet that:

1. Virtually all electronic circuits require pure dc voltage for proper operation.

2. Pure dc voltages can be obtained from batteries or properly designed power supplies.

3. A power suply consists of three major units. These are:

   a. Power transformer or ac input circuit
   b. Rectifier circuit
   c. Filter circuit

4. The simplest rectifier circuit is the half-wave rectifier.

5. For a half-wave rectifier operating into a resistive load,

   Vout dc = (v in rms) (0.45); Diode piv = (v in rms) (1.414).

6. The output ripple frequency for a half-wave rectifier circuit is equal to the power line frequency.

7. A full-wave rectifier circuit produces an average dc output voltage across a resistor that is equal to 0.9 times one half of the full rms secondary voltage of the power transformer.

8. The output ripple frequency for full-wave rectification is equal to twice the power line frequency.

9. The bridge rectifier circuit is full-wave and produces a dc output voltage across a resistive load that is equal to 0.9 times the full rms secondary voltage of the power transformer.

10. The bridge rectifier requires four rectifier diodes and each is subjected to a piv equal to the transformer rms secondary voltage multiplied by 1.414.

Key Terms

1. AVERAGE VOLTAGE

   For a full ac cycle the average voltage is equal to 0.637 times the peak voltage.

   For a rectified half cycle of ac, the average voltage equals 0.318 times the peak voltage or 0.45 times the rms voltage.

   For a rectified full-wave cycle of ac, the average voltage is equal to 0.637 times the peak voltage or 0.9 times the rms voltage.

2. BRIDGE RECTIFIER

   A full-wave rectifier circuit that uses four diodes, two of which conduct on one half of the input cycle and the other two conduct on the next half of the input cycle.

3. FULL-WAVE RECTIFIER

   A circuit that uses two diodes to convert both halves of the ac input cycle to a dc output.

4. HALF-WAVE RECTIFIER

   A circuit that uses one diode to convert one half of the ac input cycle to a dc output.

5. PEAK INVERSE VOLTAGE (piv)

   The highest voltage that appears across a diode when it is reverse biased in a rectifier circuit.

6. PEAK VOLTAGE

   The maximum voltage that occurs in an ac cycle.

7. RECTIFICATION

   The process of changing ac to dc.

8. RIPPLE VOLTAGE

   The varying or ac portion of the dc output of a power supply.

9. RIPPLE FREQUENCY

   The frequency of the ac ripple voltage in the output of a power supply. The ripple frequency is a function of the line frequency and the type of rectification used, half or full-wave.

Assignment

Answer the following multiple choice questions.

1. A power supply consists of three basic circuits wired in a specific order. The correct order is: _____

   a) Transformer; Filter; Rectifier.
   b) Filter; Transformer; Rectifier.
   c) Transformer; Rectifier; Filter.
   d) Rectifier; Filter; Transformer.

2. The simplest, most basic rectifier circuit is the: _____

   a) half-wave.
   b) full-wave.
   c) bridge.
   d) dual diode.

3. A half-wave rectifier circuit has an ac input of 30 volts at 30 Hz and operates into a 10 K resistive load. The average dc output voltage is_____ volts and the ripple frequency is _____Hz. _____

   a) 30; 30
   b) 13.5; 30
   c) 13.5; 60
   d) 27; 30

4. For an rms input of 45 volts to a half-wave rectifier operated into a 10K resistive load, the piv across the diode is approximately: _____

   a) 64 volts.
   b) 81 volts.
   c) 90 volts.
   d) 20 volts.

5. A full-wave rectifier circuit is fed by a transformer that supplies 30 volts center-tapped at 60 Hz and the rectifier circuit feeds a resistive load. The dc output is _____ volts with a ripple frequency of _____ Hz. _____

   a) 13.5; 120
   b) 30; 60
   c) 13.5; 60
   d) 15; 120

6. The advantage of bridge rectification compared to full-wave rectification is that: _____

   a) the ripple frequency is half the power line frequency.
   b) only half the ac input voltage is needed for the same dc output voltage.
   c) the ripple twice as high.
   d) none of the above.

7. A bridge rectifier has a secondary voltage of 100 volts. The piv across each diode is:

   a) 100 volts.
   b) 50 volts.
   c) 70.7 volts.
   d) 141.4 volts.

8. A bridge rectifier with an ac input of 100 volts at 400 Hz and a resistive load of 10K, has an output voltage of _____ volts and a ripple frequency of _____ .

   a) 100; 400.
   b) 90; 400.
   c) 141.4; 800.
   d) 90; 800.

Power Supply Filter Circuits

Info Sheet 3

Objectives

When you have finished this information sheet you will be able to:

1. Define what is meant by filtering.
2. Draw the circuits of L and Pi filters.
3. Calculate the ripple percentage in the power supply output.
4. Explain how a capacitive filter affects the diode conduction angle.
5. Describe the effect of a capacitive filter on the diode surge current.
6. Calculate the required value for a surge limiting resistor.
7. Define and calculate power supply regulation.

Discussion

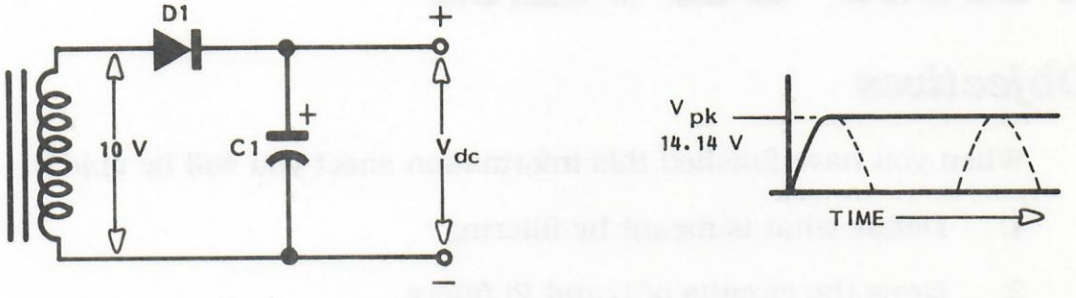
The outputs of the various rectifier circuits that were described earlier were all pulsating dc, that is dc with an ac component. Because most electronic equipment requires a pure, constant dc voltage for proper operation, the pulsating output waveforms of the rectifier circuits are not satisfactory. A FILTER CIRCUIT is added to the rectifier output to remove the ac component and leave only the dc component. The operation of a filter circuit is such that it stores energy in a capacitor when the diodes conduct and returns the energy to the circuit when the diodes are not conducting.

Capacitive Filter

The action of a CAPACITIVE FILTER is illustrated in Figure 1(a) where the output of a half-wave rectifier is applied to a capacitor. The capacitor charges to the peak value and remains charged because there is no discharge path.

The actual output waveforms with the filter capacitor in the circuit is shown in Figure 1(b) where there is no variation in output voltage; it is a constant 14.14 volts, the peak voltage. It can be shown that:

$$V_{dc\ pk} = V_{sec\ pk} = (v\ rms)\ (1.414) = (10)\ (1.414) = 14.14\ V$$



(a) HALF-WAVE RECTIFIER AND FILTER (b) FILTERED OUTPUT WAVEFORM

Figure 1 - Half-wave rectifier and capacitor filter.

Effect of Filter on the PIV

For the half-wave rectifier circuit *only*, the addition of the filter capacitor, C1, has a major effect on the value of the piv that appears across diode D1; it *doubles* the piv. Why this happens is shown in Figure 2 where the circuit of Figure 1(b) is redrawn. Other than the positioning of the components in the drawing, the two circuits are identical (electrically).

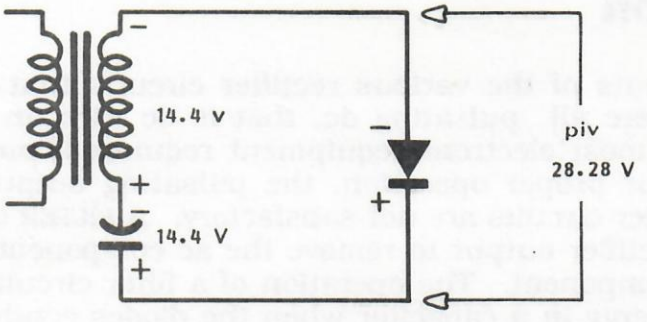


Figure 2 - Peak inverse voltage when C1 is added to the circuit.

On the first half cycle diode D1 conducts and charges C1 to the peak voltage, 14.14 volts, with the polarity shown. On the next half cycle, the polarity across the secondary reverses and the secondary voltage and the capacitor charge are in series additive. The total voltage, 28.28 volts, reverse biases the diode. This is exactly twice the piv that would appear if C1 were not in the circuit.

Effect of the Load on DC Output

When a load is placed on the output of the filtered power supply, as shown in Figure 3(a), the output waveform is affected. The output will no longer be a pure dc as shown in Figure 1(b); it will now have a RIPPLE VOLTAGE component as shown in Figure 3(b) and (c).

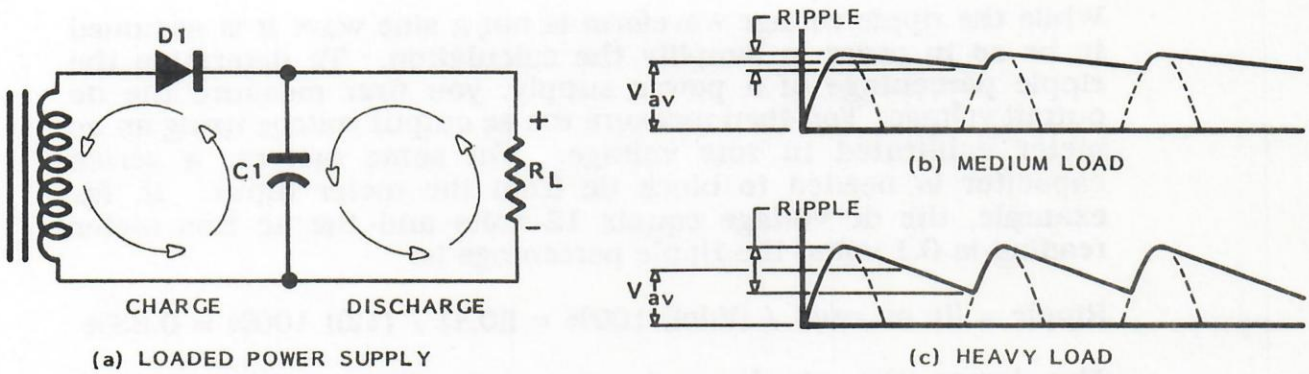


Figure 3 - Effect of the output load on ripple voltage.

On the first half cycle, C1 charges to the peak as before. Now, however, instead of remaining at the peak voltage, the capacitor starts to discharge through the load (RL) and the output voltage begins to drop. The rate of voltage drop is determined by the time constant formed by C1 and RL. Before the capacitor has completely discharged, another alternation appears to recharge the capacitor to peak and then the discharge process repeats.

If the resistance of RL is high, the long time constant causes a slow drop in the output voltage (Figure 3 (b)). When the load resistance is low, the time constant is short and the charge on C1 drops more rapidly as shown in Figure 3(c).

Examination of Figures 3(a), (b) and (c) show that as the load resistance is reduced, the:

a. load current increases
b. C1-RL time constant decreases
c. average dc level drops
d. peak-to-peak ac ripple increases.

Ripple Percentage

The effectiveness of a filter circuit in a power supply is measured in terms of how much ripple (υ ac rms) is present in the output, compared to the dc. The ripple is expressed as a percentage and calculated from:

$$\text{Ripple} = [(\upsilon \text{ ac rms}) / (\text{Vdc})]\ 100\%$$

While the ripple voltage waveform is not a sine wave it is assumed to be so in order to simplify the calculation. To determine the ripple percentage of a power supply, you first measure the dc output voltage. You then measure the ac output voltage using an ac meter calibrated in rms voltage. On some meters, a series capacitor is needed to block dc from the meter input. If, for example, the dc voltage equals 12 volts and the ac rms meter reading is 0.1 volts, the ripple percentage is:

$$\text{Ripple} = [(\upsilon \text{ ac rms}) / (\text{Vdc})]\ 100\% = [(0.1) / (12)]\ 100\% = 0.83\%$$

The lower the ripple percentage, the better the filter is performing. In an unfiltered power supply, the ripple percentage can exceed 100%. This indicates that the power supply output contains a higher ac voltage than dc voltage.

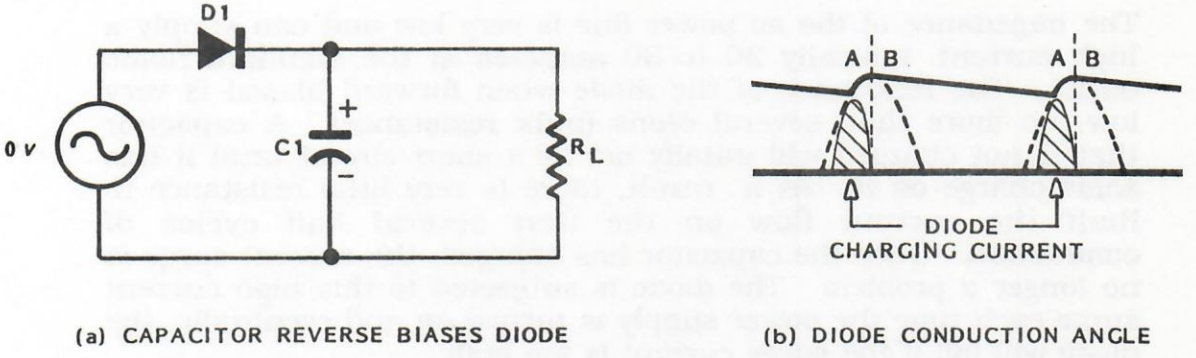
The capacitors used are usually high values and are therefore of the electrolytic type with specific lead polarities. These polarities should be observed when connecting the capacitor into the circuit. Based on the above discussions, the ripple can be improved (reduced) by increasing the size or value of the filter capacitor. The larger value capacitors affect the diode current flow as described below.

Conduction Angle and Peak Repetitive Current

In addition to affecting the ripple level, and dc output voltage and the piv of a half-wave power supply, the filter capacitor, C1, also affects the current flow through the diode. Currents in the diode will be much higher than the load current so that an understanding of diode peak currents is important to prevent diode failures. Examination of Figure 4(a) shows that the voltage on C1, if it were the only voltage in the circuit (for input = 0 volts), would reverse bias the diode.

As shown in Figure 4(a), the diode cannot conduct until the ac input voltage first exceeds the voltage on C1. When the ac input voltage does rise above the C1 voltage, the diode will then conduct. As shown in Figure 4(b), the diode can conduct only

from time A to time B of the input cycle. As a result, all the current demanded by the load must pass through the diode only during time denoted as A to B. Because the diode conducts for only a small part of the cycle, a heavy current flows to charge C1. The load then draws its current mainly from the charge on the capacitor. The period of time the diode conducts is called the CONDUCTION ANGLE and it is measured in degrees. The shorter the conduction angle, the higher the peak current and the greater the diode PEAK CURRENT rating has to be. Since this peak current occurs *every* half cycle, it is called the PEAK REPETITIVE CURRENT rating.



(a) CAPACITOR REVERSE BIASES DIODE (b) DIODE CONDUCTION ANGLE

Figure 4 - Diode conduction angle.

Diode Surge Current

Some types of power supplies requiring higher voltages do not use a power transformer in order to reduce costs. Instead, they rectify the ac power line voltage as shown in Figure 5. This results in a peak dc output voltage of 117(1.414) = 165.5 volts. When this type of power supply is used, another diode rating must be taken into consideration, the DIODE SURGE CURRENT.

The diode surge current is the peak current that flows through the diode during the first several half cycles of conduction. When the power supply is first turned on, the capacitor has no charge and therefore can be considered to be a "short." During this time, in the circuit of Figure 5(a), the only opposition to the flow of current is the:

a. impedance of the power line
b. resistance of the diode
c. opposition of the capacitor as it charges.

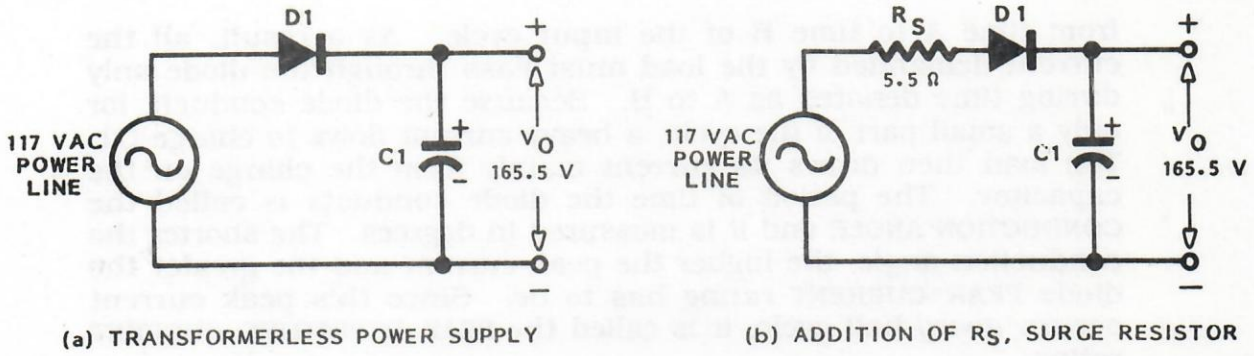


Figure 5 - Transformerless power supplies.

The impedance of the ac power line is very low and can supply a high current, typically 20 to 30 amperes at the standard home outlet. The resistance of the diode when forward biased is very low, no more than several ohms (bulk resistance). A capacitor that is not charged will initally act as a short circuit until it has some charge on it. As a result, there is very little resistance to limit the current flow on the first several half cycles of conduction. Once the capacitor has charged, the current surge is no longer a problem. The diode is subjected to this high current surge each time the power supply is turned on and eventually, the diode will fail if the surge current is too high.

To keep the surge current within the rated limits of the diode, a series resistance, called the SURGE LIMITING RESISTOR, RS, must be added between the power source and the diode as shown in Figure 5(b). The value of RS is calculated on the basis that there is no other opposition to the surge current other than RS. Given a transformerless power supply circuit as in Figure 5(b), with a 117 volt power line and a diode with a Peak Surge Current rating of 30 amperes, the surge limiting resistor will be equal to:

Surge Limiting Resistor, RS = (v pk) / (I surge)

= [(117) (1.414)] / 30 = 5.5 ohms

The value of RS should be kept as close to 5.5 ohms as possible. Less than 5.5 ohms will endanger the life of the diode and more than 5.5 ohms will degrade the power supply performance. When a power transformer is used, the surge current will be limited by the impedance of the secondary winding and most often the surge resistor will not be needed except for very high current power supplies.

The type of power supply shown in Figure 5 has a severe limitation. One side of the dc output (-) is connected directly to the power line. If the line cord is plugged into an outlet in such a

manner that the minus line is connected to the HOT side of the power line, then a 117 volt ac potential exists between the minus line and earth ground. This is a very dangerous condition and the precautions described in unit G3, Experiment 6, External Test Equipment, must be followed to prevent accidental electrocution. When troubleshooting electronic systems that use "transformerless" power supplies, such as some radio receivers and television sets, it is good safety practice to use an external "isolation-transformer" with a 1 to 1 turns ratio to prevent shock hazards due to the power line grounds.

Filtering the Full-Wave Power Supply

We have discussed the effects of adding a filter capacitor across the output of the half-wave rectifier circuit. We learned that the addition of this capacitor:

a. increased the piv across the diode.
b. caused the average dc output voltage to change with variations in the load resistance.
c. reduced the diode conduction angle.
d. created a peak repetitive diode current.
e. caused a large surge of current through the diode on the first half-cycle in a transformerless power supply.

We will now examine the effects of adding a filter capacitor across the output of a full-wave rectifier circuit. The amount of filtering required for a full-wave rectifier is less than that needed for a half-wave circuit. This is shown graphically in Figure 6.

The illustrations in Figure 6 are for a filter with the same size capacitor and load resistance (time constant) used to remove the ripple from the output of both a half-wave and full-wave rectifier circuit. The half-wave output in (a) shows a large area that requires filtering thus allowing a long discharge time for the capacitor. The output of the full-wave rectifier, shown in (b), has a much smaller area that requires filtering and allows a shorter time for the capacitor to discharge before it is recharged. This results in a lower ripple level and a higher average dc output for the full-wave circuit. Thus we see that a full-wave rectifier is more desireable than a half-wave rectifier insofar as filtering is concerned.

The addition of the filter capacitor to the full-wave circuit does not affect the piv that appears across the diodes. The piv is still equal to the peak secondary voltage of the transformer.

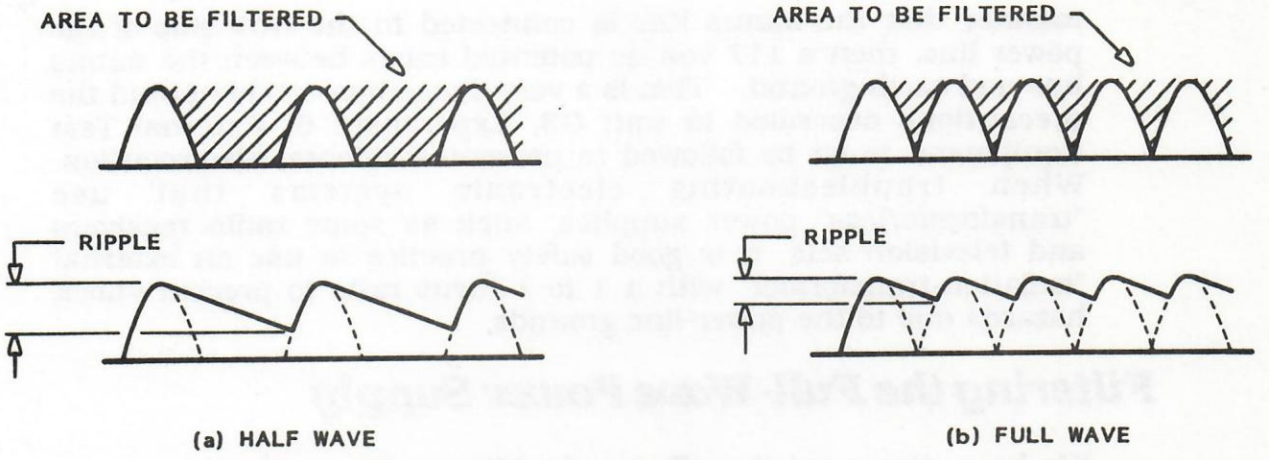


Figure 6 - Filtered output of half and full-wave rectifiers.

Because a transformer must be used for full-wave rectification, the impedance of the secondary winding will normally be sufficient to limit the surge current to a safe value.

The peak repetitive current through each diode in the full-wave circuit is lower than that in the half-wave because the two diodes "share" the current. For that reason, the peak repetitive current is *half* that of the half-wave circuit.

Inductive Filters

There are many circuits that must have an extremely low ripple level in the output of the power supply. For circuits such as these, it is sometimes necessary to add INDUCTORS to the capacitive filter circuits to further reduce ripple. An inductor can act as a filter component because it is able to store energy in its magnetic field. Because an inductor opposes change in the current flowing through it (compared to a capacitor which opposes changes in voltage across it), the inductor must be placed in series with the load as in Figure 7.

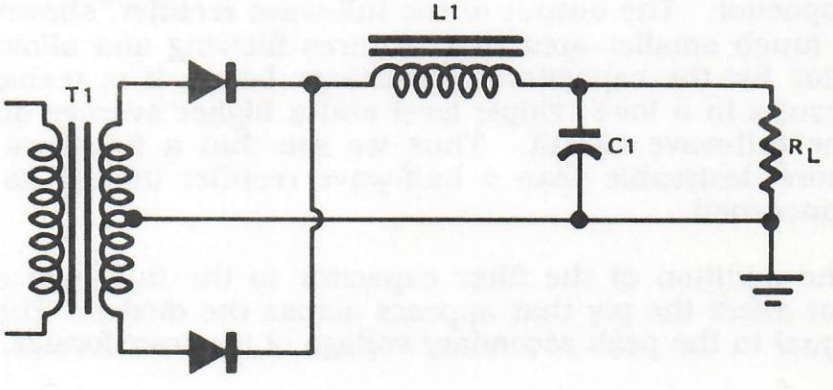


Figure 7 - A filter using both L and C components.

Because the inductor blocks or chokes off the passage of ripple, it is called a FILTER CHOKE.

In order for the filter choke, L1 in Figure 7, to be effective at ripple frequencies of 60 Hz and 120 Hz, its inductance value must be large, somewhere between 2 H (Henries) and 30 H. An increase or decrease in current flow through the choke (caused by ripple) causes a counter emf that opposes the change in current thus reducing the ripple level. The filter circuit in Figure 7, called an INVERTED L (because of its appearance in the schematic diagram), combines the filtering action of the inductor and capacitor to provide a dc output with very little ripple content.

The filter network, L1 and C1, can be viewed as a voltage divider as illustrated in Figure 8. Because the output of the rectifier circuit is pulsating dc (a combination of ac and dc voltages), consider first the effect of the filter on the ac part of the output as shown in Figure 8(a).

At 120 Hz, inductor L1 in Figure 8(a) has a reactance of 7,536 ohms and capacitor C1 has a reactance of 26.6 ohms. The two components are in series across the 120 Hz ripple voltage and act as a voltage divider. Most of the 120 Hz voltage will appear across L1 and almost none will appear across C1 which is the output.

The voltage divider action of L1 and C1 for the dc output, as shown in Figure 8(b), is very different. Inductor L1 has a very low dc resistance (50 ohms) while C1 has a very high opposition to dc (theoretically, infinite resistance). As a result the L1-C1 voltage

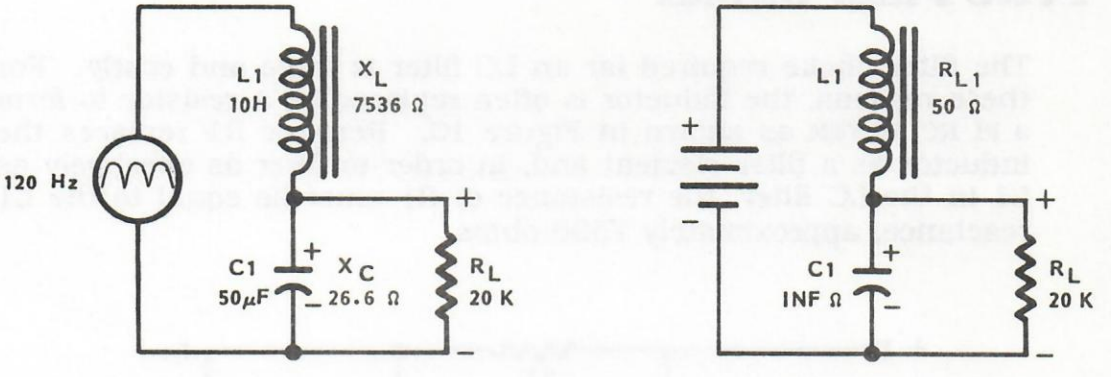


Figure 8 - LC filter voltage divider concept.

divider will drop almost all the dc voltage across C1. Thus, it may be seen that, for a pulsating dc input to the L1-C1 filter circuit, only the dc will appear across C1 while the ac will appear across L1, blocked from the output.

Pi Filter Circuits

In order to reduce the level of ripple even more than can be accomplished with an L filter, the PI FILTER as shown in Figure 9 is often used. The filter is so named because of its resemblance to the Greek letter pi, π.

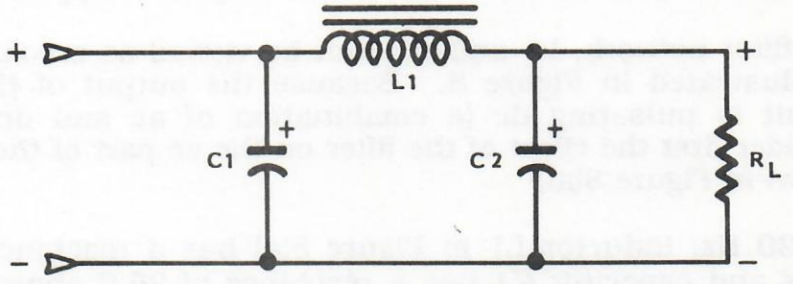


Figure 9 - A pi LC filter will provide an almost pure dc.

The use of a pi filter provides an output waveform that is almost a pure dc. The input capacitor, C1, reduces the ripple to a very low level as explained earlier. The remaining ripple voltage is then shared by L1 and C2 as explained above. The result is a virtually pure dc output.

Pi RC Filter Circuit

The filter choke required for an LC filter is large and costly. For these reasons, the inductor is often replaced by a resistor to form a Pi RC FILTER as shown in Figure 10. Resistor R1 replaces the inductor as a filter element and, in order to filter as effectively as L1 in the LC filter, the resistance of R1 must be equal to the L1 reactance, approximately 7500 ohms.

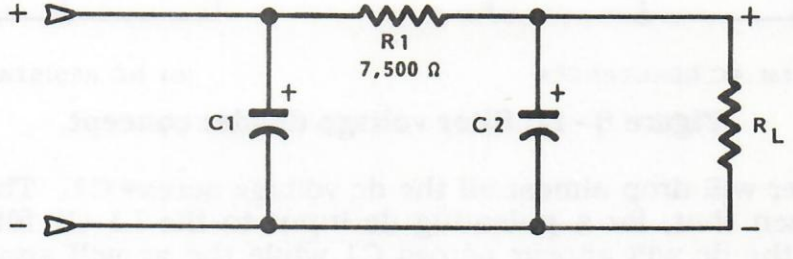


Figure 10 - Pi RC filter circuit.

Because of the high dc resistance of R1 (7500 ohms compared to 50 ohms for L1) there will be a large voltage drop in the dc output voltage with big changes in output voltage each time the load current varies. To minimize this swing in output voltage, the value of R1 is reduced to under 100 ohms but this also reduces the filtering effectiveness of the pi RC circuit. The filtering action is still better with the 100 ohms and two capacitors than with only one capacitor.

Power Supply Regulation

Decreasing the load resistance connected across the output of power supply causes an increase in the load current, a decrease in the average dc output voltage and an increase in the ripple voltage as previously discussed and illustrated in Figure 3. As the load resistance is lowered, the RC time constant of the filter circuit (resistance of the load and capacitance of the filter) is reduced permitting the filter capacitor to discharge more rapidly.

The ability of a power supply to maintain a constant dc output voltage for varying load currents is called REGULATION. It is measured in percentage and expressed as:

Regulation = [(VNL - VFL) / (VFL)] 100%

Where: VNL = output voltage with no load

VFL = output voltage with full load (maximum drain)

Given a power supply with a no-load output voltage of 12 volts and a full-load voltage of 11.8 volts, the regulation percentage is:

Regulation = [(VNL - VFL) / (VFL)]100%

Regulation = [(12 - 11.8) / (11.8)]100% = 1.69 %

When it is necessary to operate a circuit that can tolerate no voltage variations, a special REGULATOR CIRCUIT must be added to the power supply as shown in Figure 11. A simple regulator circuit uses a Zener Diode. Advanced transistorized regulators using discrete transistors and components and Integrated Circuit regulators are covered in a later unit. All regulator circuits, in addition to stabilizing the output voltage, also reduce ripple voltage levels so that much less filtering is required.

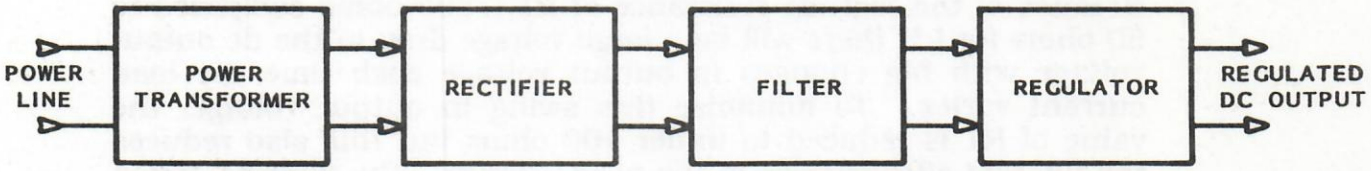


Figure 11 - Block diagram of a regulated power supply.

Power Supply Output Resistance

We normally specify the regulation percentage of a power supply for the maximum load current for which the power supply was designed. If the supply were operated at a current lower than the maximum allowable, it would exhibit improved regulation characteristics. Another way of specifying the regulation of a power supply is to give the supply's output impedance or resistance (Ro) which is independent of the load current. This is illustrated in Figure 12.

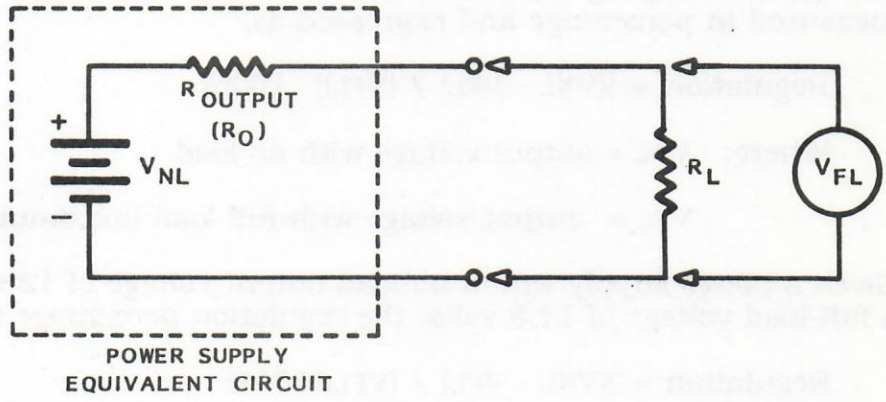


Figure 12 - Power supply equivalent circuit showing the internal resistance, Ro.

Applying the familiar voltage divider formula, the output voltage, VFL, is given by:

$$VFL = (VNL)\ [(RL) / (Ro + RL)]$$

By manipulating the equation we have:

$$(Ro + RL)(VFL) = VNL\ RL$$

$$Ro\ VFL = RL(VNL - VFL)$$

$$Ro = RL\ [(VNL - VFL) / (VFL)]$$

Because (V_{NL} - V_{FL}) / (V_{FL}) is equal to the regulation, we can state that:

$$R_o = (R_L)\ (\text{Regulation})$$

where R_L is the resistance required to draw the maximum allowable current (V_{FL}/I_{FL}).

Thus, if a power supply has an output voltage of 12 volts, a stated regulation of 1% (a factor of 0.01) and a maximum allowable current of 3 amperes, then:

$$R_o = (12/3)\ (0.01)$$

$$R_o = 0.04 \text{ ohms}$$

Diode Characteristics Summary

In Information Sheet 1, Solid State PN Junctions, we discussed only three major characteristics of the diode, I_F, the maximum allowable forward current, I_R, the maximum allowable reverse current and V_R, the maximum allowable reverse voltage, also called piv. In this discussion of power supply filters, two more diode characteristics were introduced; surge current and peak repetitive current. A partial extract from the 1N4002 diode specification sheet is shown in Figure 13. The 1N4002 is the silicon rectifier diode (D1 to D4) used on the Ed Lab Trainer. The data sheet covers several different diodes but we are only interested in the 1N4002.

The piv is defined as both V_{RM} (V reverse maximum) and V_R (V reverse), for different temperature conditions.

The forward current, I_F, is defined as I_O (output) and called the "Average Rectified Forward Current."

The Peak Repetitive Current rating is labeled I_{FR} (Forward Repetitive Maximum) and called the "Repetitive Peak Forward Current."

The diode Surge Current is labeled I_{FSM} (Forward Surge Maximum) and is called the "Peak Surge Current.

Because this diode is designed for power supply service, all specifications are for 60 Hz as indicated in Notes 1 and 3. As a result, no reverse recovery time is noted for this type of diode.

High Frequency Diodes

We know from Experiment 1, Diode Operation, that the 1N4001 will operate satisfactorily up to 1kHz before the trr begins to affect the rectification efficiency. Diodes used for communications or computer circuits must be fast acting and so, for these diodes, the trr is critical. A partial extract from the 1N4305 Switching Diode Specification sheet is shown in Figure 14. Observe that the rating criteria is different from that of the rectifier diode. There are no peak rectifier current or surge current ratings. Instead there is a CT rating (2 picofarads) because the greater the diode capacitance the slower it will be to change current. Note further that a trr rating (2 nanoseconds) is given.

Conclusions

We have learned from this information sheet that:

1. The power supply consists of three major blocks. These are the Power Transformer, Rectifier and Filter circuit.

2. Virtually all electronic circuits require a pure dc voltage for proper operation.

3. Pure dc voltages can be obtained from batteries or properly designed power supplies.

4. A filter circuit that removes the pulsations from the power supply dc output may consist of a capacitor only, a capacitor and inductor in an L configuration or two capacitors and an inductor in a pi configuration.

5. The ac present in the dc output of a power supply is called ripple and is measured as a percentage of the output.

   $$\text{Ripple} = [(\text{Vac rms}) / (\text{Vdc})]100\%$$

6. The diode conduction angle in a filtered power supply is less than 180 degrees and the peak diode current during conduction is greater than the average dc load current.

7. A diode has a rating defined as the "Repetitive Peak Forward Current" which indicates the peak current the diode can handle during the conduction angle of each cycle.

8. The change in output voltage as the load resistance or current is changed is measured as Regulation and defined as follows.

   $$\text{Regulation} = [(V_{NL} - V_{FL}) / (\text{Vdc})]100\%$$

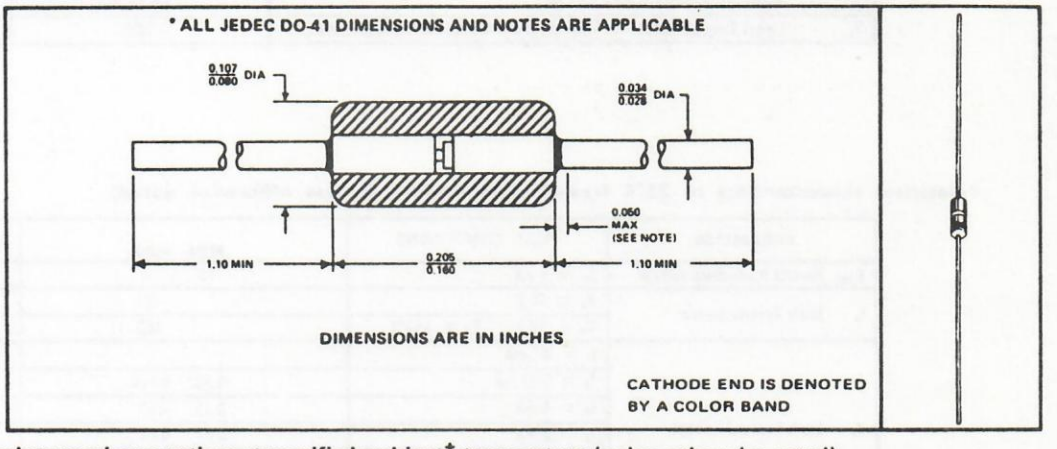
TYPES 1N4001 THRU 1N4007
SILICON RECTIFIERS

50-1000 VOLTS • 1 AMP AVERAGE

- Rugged Double-plug Construction
- Hermetic Case
- 30-Amp Surge Rating

description and mechanical data

These one-amp rectifier diodes are the product of combining the best of both silicon material processing and packaging technologies. The silicon die is a mesa oxide-passivated structure which has additional nitride passivation and glass passivation over the junction. Years of volume production have shown the double-plug package to have the highest inherent mechanical integrity of all hermetic-case diodes.


*ALL JEDEC DO-41 DIMENSIONS AND NOTES ARE APPLICABLE
0.107 / 0.080 DIA
0.034 / 0.028 DIA
0.050 MAX (SEE NOTE)
1.10 MIN
0.205 / 0.160
1.10 MIN
DIMENSIONS ARE IN INCHES
CATHODE END IS DENOTED BY A COLOR BAND

***absolute maximum ratings at specified ambient† temperature (unless otherwise noted)**

		1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	UNIT
V_{RM}	Peak Reverse Voltage from −65°C to 175°C (See Note 1)	50	100	200	400	600	800	1000	V
V_R	Steady State Reverse Voltage from 25°C to 75°C	50	100	200	400	600	800	1000	V
I_O	Average Rectified Forward Current from 25°C to 75°C (See Notes 1 and 2)	1							A
I_{FRM}	Repetitive Peak Forward Current, 10 Cycles, at (or below) 75°C (See Note 3)	10							A
I_{FSM}	Peak Surge Current, One Cycle, at (or below) 75°C (See Note 3)	30							A
$T_{A(opr)}$	Operating Ambient Temperature Range	−65 to 175							°C
T_{stg}	Storage Temperature Range	−65 to 200							°C
	Lead Temperature 3/8 Inch from Case for 10 Seconds	350							°C

NOTES: 1. These values may be applied continuously under single-phase, 60-Hz, half-sine-wave operation with resistive load.
2. This rectifier is a lead-conduction-cooled device. At (or above) ambient temperatures of 75°C, the lead temperature 3/8 inch from case must be no higher than 5°C above the ambient temperature for these ratings to apply.
3. These values apply for 60-Hz half sine waves when the device is operating at (or below) rated values of peak reverse voltage and average rectified forward current. Surge may be repeated after the device has returned to original thermal equilibrium.

*JEDEC registered data. This data sheet contains all applicable registered data in effect at the time of publication.

†The ambient temperature is measured at a point 2 inches below the device. Natural air cooling is used.

Figure 13 - Partial extract from the 1N4002 diode data sheet, courtesy of Texas Instruments Inc.

TYPE 1N4305
SILICON SWITCHING DIODE

FAST SWITCHING DIODE

- Rugged Double-Plug Construction

Electrical Equivalents

***absolute maximum ratings at 25°C free-air temperature (unless otherwise noted)**

			UNIT
V_{RM}	Peak Reverse Voltage	75	V
P	Continuous Power Dissipation at (or below) 25°C Free-Air Temperature (See Note 1)	500	mW
T_{stg}	Storage Temperature Range	–65 to 200	°C
T_L	Lead Temperature 1/16 Inch from Case for 10 Seconds	300	°C

***electrical characteristics at 25°C free-air temperature (unless otherwise noted)**

PARAMETER		TEST CONDITIONS	MIN	MAX	UNIT
$V_{(BR)}$	Reverse Breakdown Voltage	I_R = 5 μA	75		V
I_R	Static Reverse Current	V_R = 50 V		0.1	μA
		V_R = 50 V, T_A = 150°C		100	μA
V_F	Static Forward Voltage	I_F = 0.1 mA			V
		I_F = 0.25 mA	0.505	0.575	V
		I_F = 1 mA	0.55	0.65	V
		I_F = 2 mA	0.61	0.71	V
		I_F = 10 mA	0.70	0.85	V
		I_F = 100 mA			V
α_{V_F}	Forward Voltage Temperature Coefficient	I_F = 10 μA to 10 mA, See Note 2		3	mV/°C
C_T	Total Capacitance	V_R = 0, f = 1 MHz		2	pF

***operating characteristics at 25°C free-air temperature**

PARAMETER	TEST CONDITIONS	MIN	MAX	UNIT
t_{rr} Reverse Recovery Time	I_F = 10 mA, I_{RM} = 10 mA, i_{rr} = 1 mA, R_L = 100 Ω,	4	4	ns
	I_F = 10 mA, V_R = 6 V, i_{rr} = 1 mA, R_L = 100 Ω,	2	2	ns
η, Rectification Efficiency	V_r = 2 V, R_L = 5 kΩ, C_L = 20 pF, Z_{source} = 50 Ω, f = 100 MHz	45 %		

Figure 14 - Partial extract from the 1N4305 switching diode, courtesy of Texas Instruments Inc.

Key Terms

1. CONDUCTION ANGLE

   The number of degrees of the ac input cycle over which the diode will conduct in the forward direction.

2. FILTER CHOKE

   An iron core inductor, placed in series with the power supply load, that offers high opposition to ac but very little opposition to dc.

3. FILTER CIRCUIT

   A combination of L, C and R components, used to remove the ac component from the output of a rectifier circuit.

4. LC FILTER

   A filter circuit, used on the output of a rectifier circuit, that consists of an inductor and one or more capacitors. Its function is to remove the ripple voltage from the dc output.

5. PEAK INVERSE VOLTAGE (piv)

   The highest voltage that appears across a rectifier diode in the non-conducting direction (reverse biased).

6. PEAK REPETITIVE CURRENT

   The peak current that flows through the diode each half cycle during the diode conduction angle. The narrower the conduction angle, the higher the peak repetitive current.

7. PI FILTER

   A power supply filter formed from RC or LC components configured as the Greek letter pi.

8. RC FILTER

   A filter used on the output of a rectifier circuit that consists of resistors and capacitors. The configuration is always a pi with the resistor acting in place of the inductor filter element.

9. REGULATION PERCENTAGE

The ability of a power supply to maintain a constant output voltage despite variations in load current. Normally measured in percentage, it is determined from:

$$\text{Regulation} = [(V_{NL} - V_{FL}) / (V_{FL})]100\%$$

10. RIPPLE VOLTAGE

The varying portion of the dc output voltage of a power supply. It may be measured by placing an ac voltmeter across the power supply output but with a series blocking capacitor to stop the dc.

11. RIPPLE FREQUENCY

The frequency of the ac ripple voltage present in the output of a power supply. The ripple frequency is a function of the power line frequency and the type of rectification used, half or full-wave.

12. RIPPLE PERCENTAGE

A method of measuring the ripple level as compared to the dc output voltage, expressed as a percentage.

$$\text{Ripple} = [(\text{Vac rms}) / (\text{Vdc}) \quad 100\%$$

13. SURGE CURRENT

The current conducted by the diode on the first half cycle to charge the filter capacitor.

Assignment

Answer the following multiple choice questions.

1. The output of a power supply measures 27 volts dc and 0.1 volts ac rms. The ripple percentage is approximately: _____

   a) 27%
   b) 0.1%
   c) 0.37%
   d) 2.7%

2. The filter circuit that will produce the lowest ripple in the output of a power supply, with all other factors being equal, is the: _____

   a) LC L configuration.
   b) LC pi configuration.
   c) RC pi configuration.
   d) all the same %.

3. As the load current drained from a power supply is increased, the ripple percentage will _____and the output voltage will_____. _____

   a) decrease; increase
   b) decrease; decrease
   c) increase; increase
   d) increase; decrease

4. The narrower the diode conduction angle, the higher the: _____

   a) average power supply load current.
   b) peak diode current.
   c) diode surge current.
   d) diode piv.

5. A half-wave rectifier and filter circuit is operated directly from the 117 volt power line (no transformer). The rectifier diode has a maximum allowable surge current of 12 amperes. The surge limiting resistor must be _____ ohms and it will dissipate _____ watts during the peak surge current. _____

   a) 13.75; 1985
   b) 10; 120
   c) 12; 120
   d) none of the above.

6. The pulsating dc output of a half-wave rectifier circuit: _____

   a) is more difficult to filter than the output of a full-wave rectifier circuit.
   b) has a ripple frequency equal to the line frequency.
   c) when applied to a capacitor filter, will double the piv.
   d) all of the above.

7. A full-wave power supply uses a pi LC filter circuit. The most likely value of inductance for the filter choke is: _____

   a) 20 H.
   b) 100 mH.
   c) 2.5 mH.
   d) 1,000 mH.

8. The advantage of a pi RC filter circuit over a pi LC filter circuit is: _____

   a) a higher voltage drop across the filter resistor.
   b) the elimination of the need for a filter choke.
   c) the need for smaller value filter capacitors.
   d) all of the above.

Voltage Multiplier Circuits

Info Sheet 4

Objectives

When you finish this information sheet you will be able to:

1. Draw the circuit of and explain the operation of a half-wave voltage doubler.
2. Draw the circuit of and explain the operation of a full-wave voltage doubler.
3. Draw the circuit of and explain the operation of a voltage tripler.

Discussion

When a circuit requires a dc operating voltage that is greater than the available ac voltage source, a VOLTAGE MULTIPLIER circuit must be used. The most frequently encountered multiplier is the VOLTAGE DOUBLER of which there are two types, the half-wave and full-wave.

Half-Wave Voltage Doubler

The circuit of a half-wave voltage doubler is shown in Figure 1. It consists of two half-wave rectifier circuits. The first half-wave circuit consists of C1 and D1.

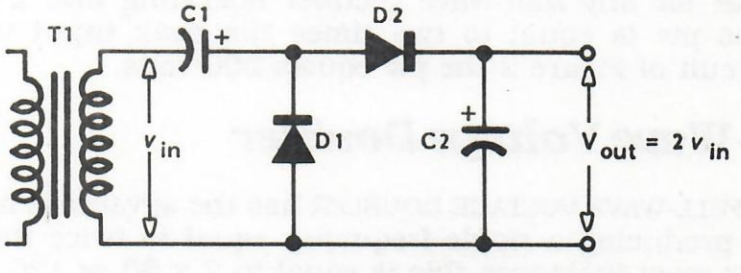


Figure 1 - Half-wave voltage doubler circuit.

The operation of the voltage doubler is described in Figures 2(a) and (b). On the first half of the input cycle, when point A of T1 is negative, only diode D1 conducts and charges C1 to peak value of v in.

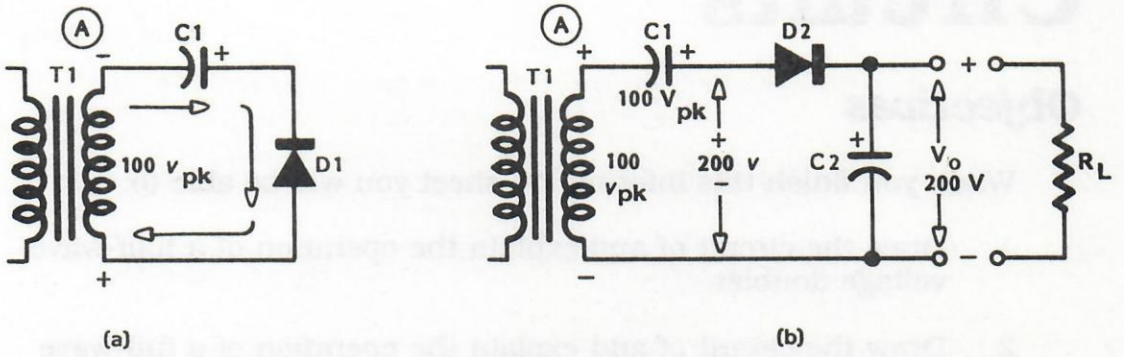


Figure 2 - Half-wave voltage doubler operation.

On the second half of the ac input cycle, point A on T1 is positive. The peak voltage across the T1 secondary is now in series aiding with the voltage on C1 and since both are 100 volts, the total voltage applied to the D2-C2 circuit is 200 volts for an output of 200 volts dc. In Figure 2(b), it is seen that capacitor C1 acts like a series "battery" in a simple half-wave rectifier circuit to double the dc voltage. This represents the peak dc output voltage and will drop to close to twice the value of the rms input voltage, 70.7 volts, when current is drained. The larger the capacitance values of C1 and C2 the better the output voltage will hold as the current drain is increased.

Ripple and PIV

As with any other half-wave rectifier circuit, the half-wave doubler has a ripple frequency equal to the power line frequency, in most instances 60 Hz.

The piv seen by each diode in the voltage doubler is the same a that for any half-wave rectifier operating into a capacitive filter. The piv is equal to two times the peak input voltage. For the circuit of Figure 2 the piv equals 200 volts.

Full-Wave Voltage Doubler

A FULL-WAVE VOLTAGE DOUBLER has the advantage over the half-wave of producing a ripple frequency equal to twice the line frequency. For most instances this is equal to 2 x 60 or 120 Hz. In addition, a full-wave voltage doubler will maintain a more constant output

voltage as the current drain is increased. A typical full-wave voltage doubler is shown in Figure 3.

This circuit is actually two half-wave rectifiers producing positive and negative outputs. The output is taken across both and is thus doubled as they are in series aiding.

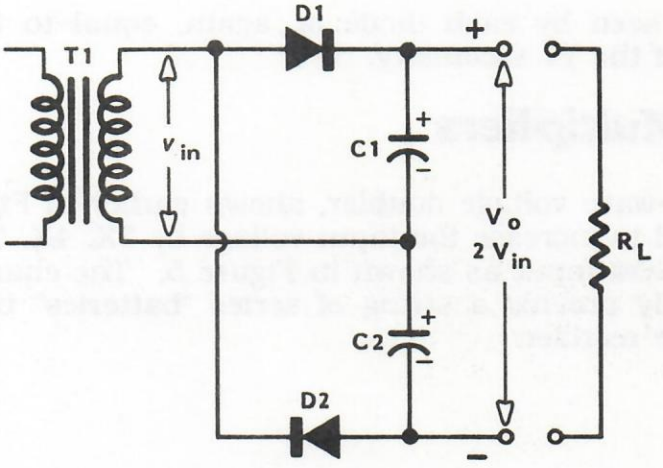


Figure 3 - Full-wave voltage doubler circuit.

The charging paths are reviewed below. The full-wave voltage doubler circuit operation is described in Figures 4 (a) and (b). In Figure 4(a), on the first half cycle, point A on T1 is positive. Diode D1 conducts to charge C1 to the peak of the input voltage, 100 volts, with the output polarity shown. Diode D2 is reverse biased, does not conduct and so D2 and C2 are effectively out of the circuit for the moment.

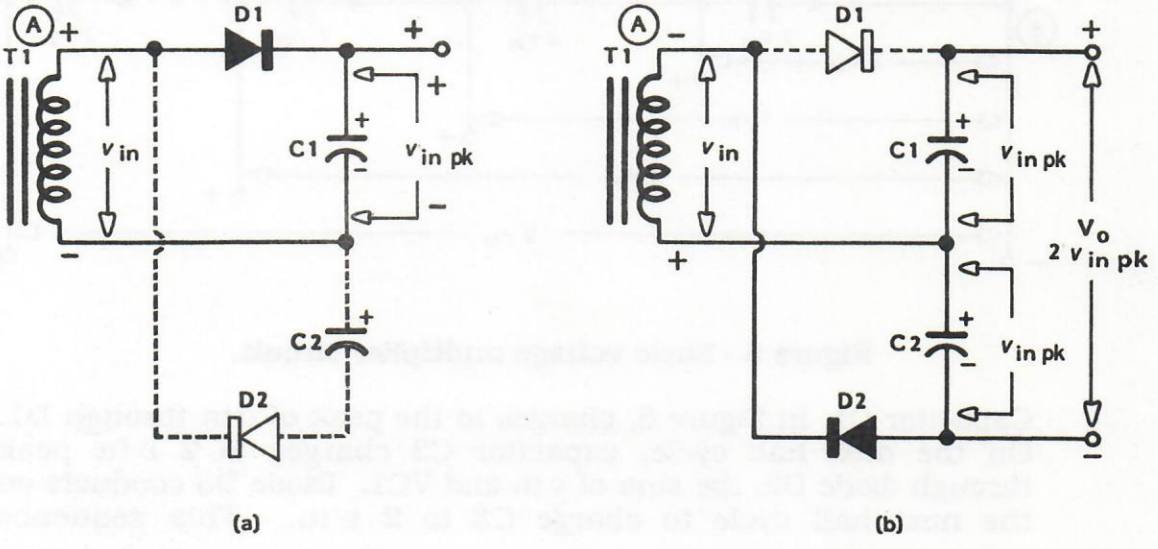


Figure 4 - Full-wave voltage doubler operation.

On the next half cycle, point A reverses polarity and is negative. Diode D1 is now reverse biased while diode D2 is forward biased. Capacitor C2 is now charged to the peak input voltage. The total voltage between the two output terminals is equal to the sum of the charges on C1 and C2, each of which is charged to the peak value of v in. Because C1 and C2 are wired series aiding, Vo equals 2 x v in pk.

The piv seen by each diode is, again, equal to twice the peak voltage of the T1 secondary.

Voltage Multipliers

The half-wave voltage doubler, shown earlier in Figure 1, can be expanded to increase the input voltage by 3X, 4X, 5X, 6X, 7X and 8X the peak input as shown in Figure 5. The charged capacitors essentially provide a string of series "batteries" before the final half-wave rectifier.

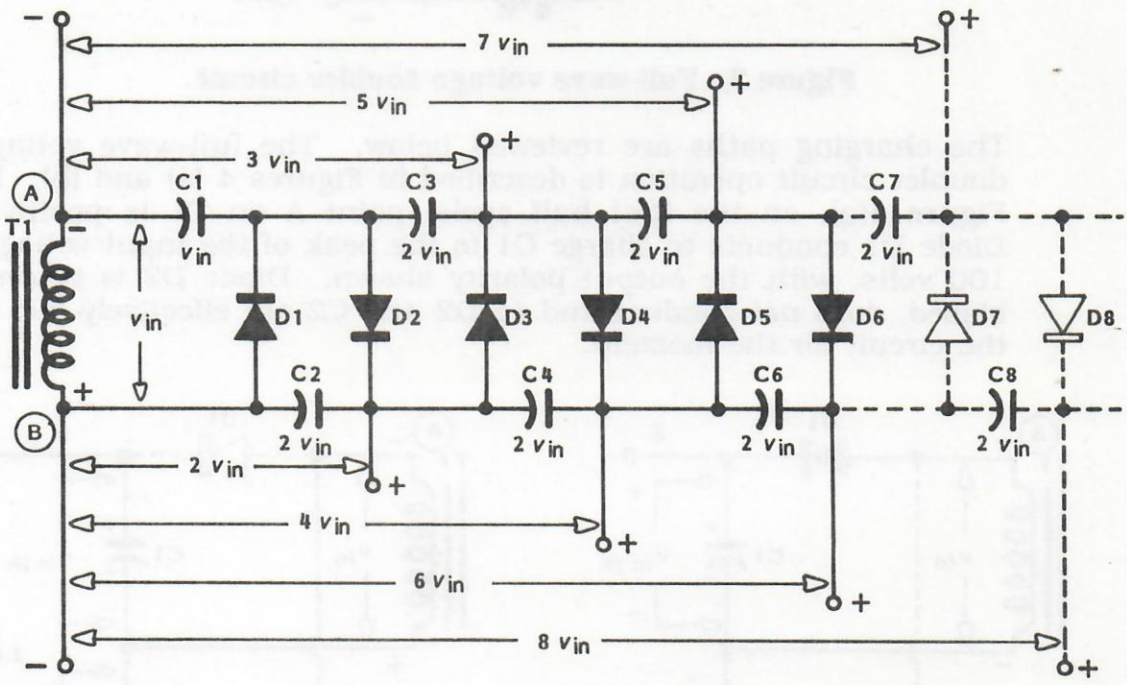


Figure 5 - Basic voltage multiplier circuit.

Capacitor C1, in Figure 5, charges to the peak of v in through D1. On the next half cycle, capacitor C2 charges to 2 v in peak through diode D2, the sum of v in and VC1. Diode D3 conducts on the next half cycle to charge C3 to 2 v in. This sequence

continues with diodes D1, D3, D5 and D7 conducting on the negative half cycles and diodes D2, D4, D6 and D8 conducting on the positive half cycles. The output voltages may be taken from the points indicated in Figure 5. For the odd multiples of v in, the negative terminal at A must be used and for even multiples of v in, the point B negative terminal must be used.

Regulation and ripple percentages also apply to voltage multiplier circuits used with varying loads.

Conclusions

We have learned from this information sheet that:

1. An unloaded half-wave voltage doubler will produce a dc output voltage equal to twice the peak ac input.

2. The ripple frequency in the output of a half-wave voltage doubler is twice the power line frequency and the piv on each diode is twice the peak ac input voltage.

3. For the full-wave voltage doubler, the unloaded output voltage is equal to twice the peak ac input voltage, the ripple frequency equals twice the power line frequency and the piv is equal to twice the peak ac input voltage.

4. The half-wave voltage doubler circuit can be expanded to increase the input voltage by x3, x4, x5, x6, x7, *etc.*. For each multiple, another diode and capacitor must be added.

5. For each multiple of increase, while the output voltage is increased, the regulation characteristic becomes poorer.

Key Terms

1. FULL-WAVE RECTIFICATION

   A circuit, using diodes, that converts both halves of the ac cycle to a dc output voltage.

2. HALF-WAVE RECTIFICATION

   A circuit, using diodes, that converts one half of the ac cycle to a dc output voltage.

3. PEAK INVERSE VOLTAGE (piv)

   The highest voltage that appears across a rectifier diode when it is reverse biased.

4. PEAK VOLTAGE

   The maximum voltage that occurs in an ac cycle.

5. RIPPLE VOLTAGE

   The varying portion of the dc output voltage of a power supply.

6. RIPPLE FREQUENCY

   The frequency of the ripple voltage in the output of a power supply. The ripple frequency is a function of the power line frequency and the type of rectification, half-wave or full-wave.

7. VOLTAGE DOUBLER

   A power supply circuit in which the dc output voltage is twice the ac input voltage.

8. VOLTAGE MULTIPLIER

   A power supply circuit that produces a dc output voltage that is a multiple of the ac input voltage.

9. VOLTAGE QUADRUPLER

   A circuit that produces a dc voltage equal to four times the ac input voltage.

10. VOLTAGE TRIPLER

    A circuit that produces a dc voltage equal to three times the ac input voltage.

Assignment

Answer the following multiple choice questions.

1. When the ac input voltage available is not enough to produce the required dc output voltage, the circuit that may be used to obtain the desired dc voltage is a voltage: _____

   a) doubler.
   b) tripler.
   c) quadrupler.
   d) all of the above.

2. The ripple frequency of a full-wave voltage doubler is: _____

   a) equal to the line frequency.
   b) twice the line frequency.
   c) 400 Hz.
   d) none of the above.

3. The ripple frequency of a voltage tripler is: _____

   a) equal to the line frequency.
   b) twice the line frequency.
   c) triple the line frequency.
   d) none of the above.

4. A full-wave voltage doubler is powered from the 117 volt, 60 Hz line. The no-load output voltage is _____volts and the ripple frequency is _____Hz. _____

   a) 117; 60
   b) 234; 120
   c) 331; 60
   d) 331; 120

5. A voltage quadrupler is operated from a 36 volt, 60 Hz secondary winding. Its no-load output voltage is _____volts and the ripple frequency is _____Hz. _____

   a) 204; 60 Hz.
   b) 204; 120 Hz.
   c) 72; 60 Hz.
   d) 144; 120 Hz.

Diode Testing and Troubleshooting

Info Sheet 5

Objectives

When you have finished this information sheet you will be able to:

1. Identify diodes by their case shape and determine the cathode terminal of each type of diode case.
2. Describe the method of testing a diode using an analog ohmmeter, a digital VOM and a voltmeter and voltage source.
3. List the steps to follow when troubleshooting a defect in a power supply based on fault symptoms and measurements at key test points.

Discussion

It is possible for diodes that are used in electronic equipment to fail thus causing the circuit to operate improperly or not operate at all. The troubleshooting procedure used will, after several steps, lead you to the suspected diode, at which point you will have to test that diode to see if it is defective. Some typical diode case shapes are shown in Figure 1 along with the diode symbol to identify polarity (cathode and anode).

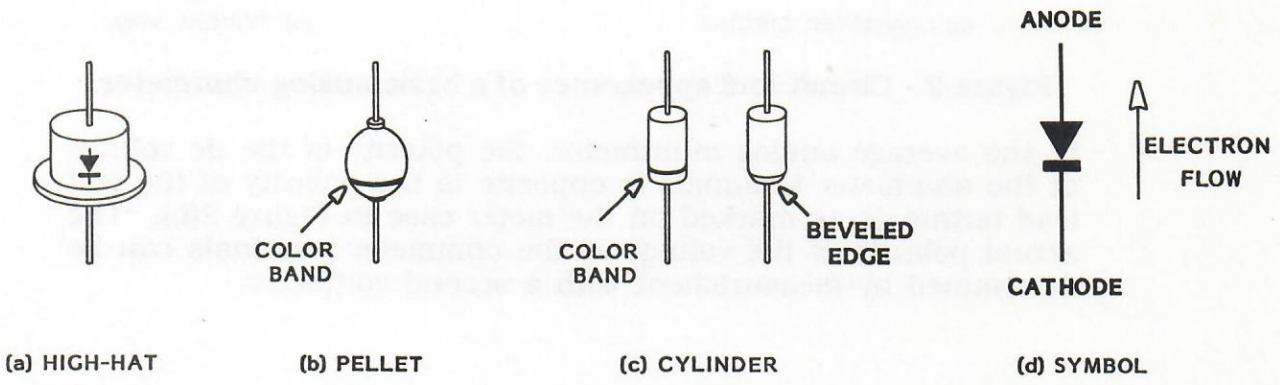


Figure 1 - Typical diode packages and their symbol. The most frequently used cases are the cylinders, type (c).

Diode Testing

When a diode is thought to be defective, it may be tested by one of several methods. Sometimes, when testing a diode, it is necessary that at least one end be disconnected from the circuit. This will prevent the other circuit components from forming a shunt path across the diode causing false ohmmeter readings.

Recall from an earlier experiment in Unit E4, Experiment 27, Ohmmeter Circuits, that an analog ohmmeter circuit contains its own internal voltage source, usually a battery as low as 1.5 volts or as high as 15 volts. When using an analog ohmmeter to test a diode, it is this internal voltage source that is used to forward and reverse bias the diode. For this reason it is necessary to know the polarity of the voltage that appears across the ohmmeter leads as in Figure 2.

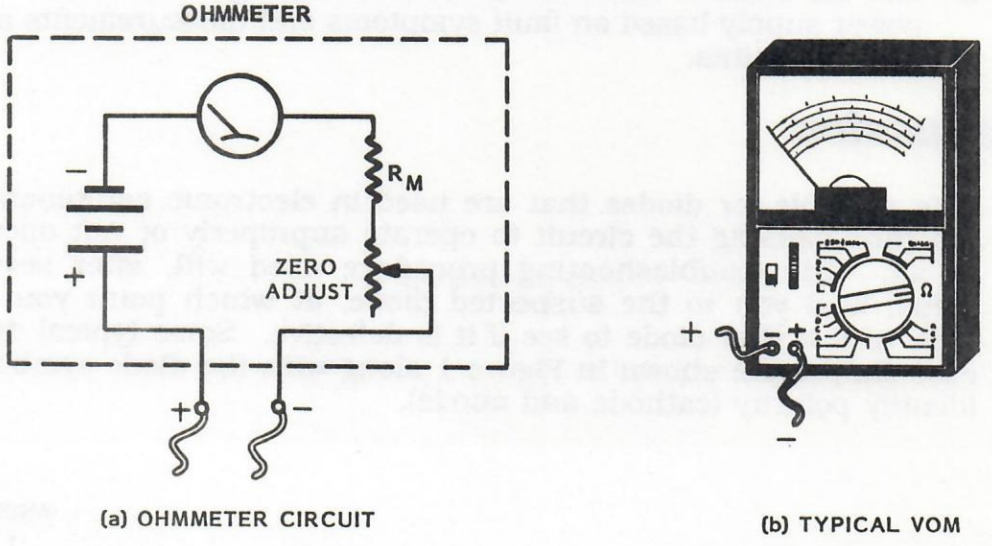


Figure 2 - Circuit and appearance of a basic analog ohmmeter.

In the average analog multimeter, the polarity of the dc voltage at the ohmmeter terminals is opposite to the polarity of the test lead terminals as marked on the meter case in Figure 2(b). The actual polarity of the voltage at the ohmmeter terminals can be determined by measurement with a second voltmeter.

Once the ohmmeter polarity is known, a diode can be tested as shown in Figures 3(a) and (b). In Figure 3(a) the internal voltage source of the ohmmeter is forward biasing the diode and the resultant reading will be low, anywhere from 10 to 100 ohms depending on the ohmmeter range (R x 1 or R x 10). The exact value of resistance is not important.

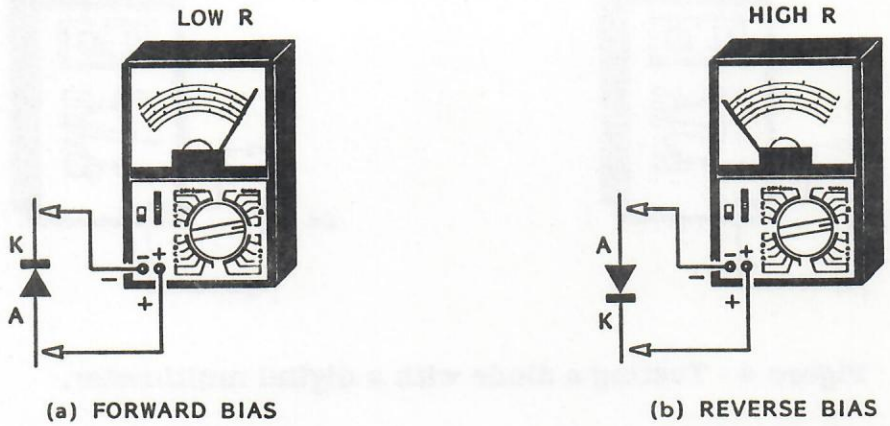


Figure 3 - Testing a diode using an analog ohmmeter.

In Figure 3(b) the applied voltage has been reversed and, as a result, the diode is now reverse biased. If the diode is silicon, the resistance reading will be infinite; if germanium, some small leakage will show; typically 10 megohms.

A *shorted* diode will cause a low resistance reading in *both* directions while a diode that shows a *high* resistance in both directions is *open*.

Digital Multimeter Tests

The voltage across the test leads of a digital ohmmeter is frequently too low to forward bias a germanium or silicon diode junction. Because of this, resistance measurements of a diode with a digital ohmmeter often shows the junction to be open in both directions even though the diode may be good. Many digital multimeters, therefore, have a special provision for testing diodes, a DIODE TEST position on the meter Function Switch. Not only will this test indicate if a diode is good or bad, it will also

indicate if the diode is germanium or silicon. A good silicon junction will read close to 0.7 volts on the meter read-out while a good germanium device will read close to 0.3 volts as shown in Figure 4.

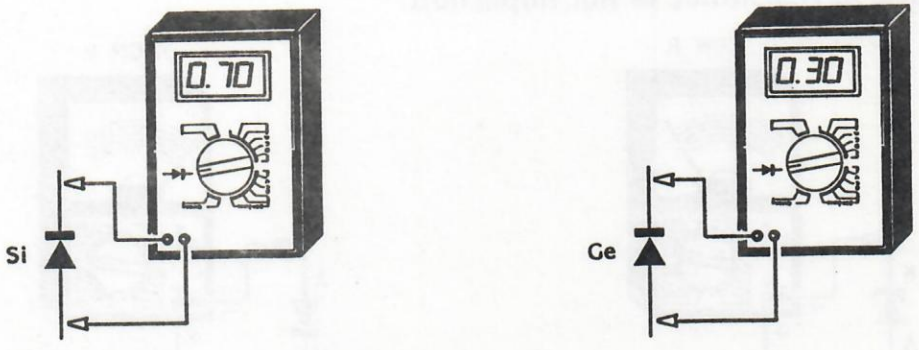


Figure 4 - Testing a diode with a digital multimeter.

When the diode under test is shorted, the digital read-out will be zero volts. If the diode under test is open, the meter will read whatever it normally indicates when the test leads are not connected. Typical readings for the reverse or open connection are 3 volts, 1300 mV or OL (indicating Overload).

Diode Testing With a Voltage Source

A diode junction may be tested using a voltage source and a voltmeter as shown in Figure 5. When the diode junction is forward biased, the voltmeter will read the source voltage Vs, less the diode junction drop 0.3 volts or 0.7 volts. The internal resistance of the voltmeter will be between 5K to 100K so that the current through the diode is limited to a safe value.

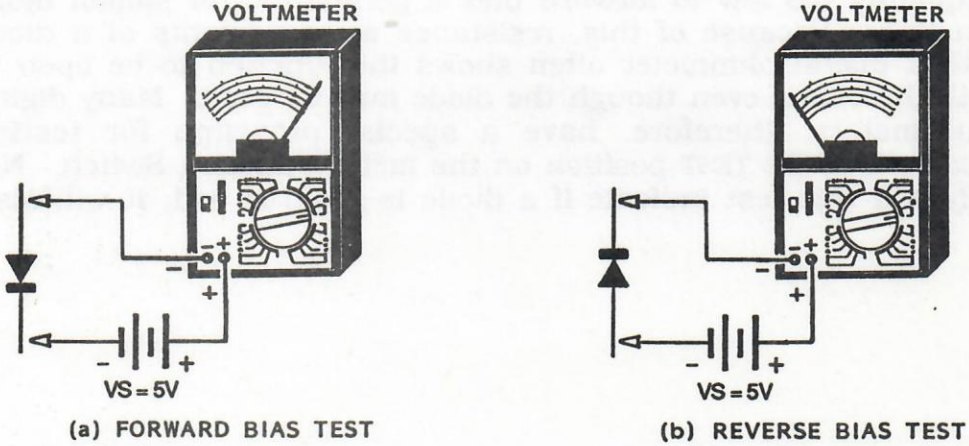


Figure 5 - Testing a diode using a voltage source and voltmeter.

The reverse bias test shown in Figure 5(b) will produce a voltage reading only if the junction is shorted or has a "leakage current." Some small amount of leakage is normal for germanium diodes.

Troubleshooting Techniques

The diodes that fail most often are those used in the power supply circuits where high currents and voltages are encountered. Because of the high currents, considerable heat is generated and this heat is harmful not only to diodes but all the components in the power supply. As a result, power supply component failures are the most common cause of equipment malfunction. Whenever a piece of equipment fails to operate, the power supply is the logical starting point.

As shown in earlier experiments in this unit, a power supply consists of a power transformer, diodes, capacitors and resistors. We have learned earlier how to test these other components and now we will apply these test procedures to the power supply circuit. A logical test procedure should be used to locate a fault as opposed to a random check of individual parts.

A full-wave power supply circuit is shown in Figure 6. The first step in troubleshooting this circuit is to test the output voltage. This may be done with a voltmeter but checking the output with an oscilloscope has an advantage. Not only will it show the dc output voltage but it will also indicate the level of ripple. If the dc level and ripple level are normal, the power supply is working properly and you will have to look elsewhere for the fault.

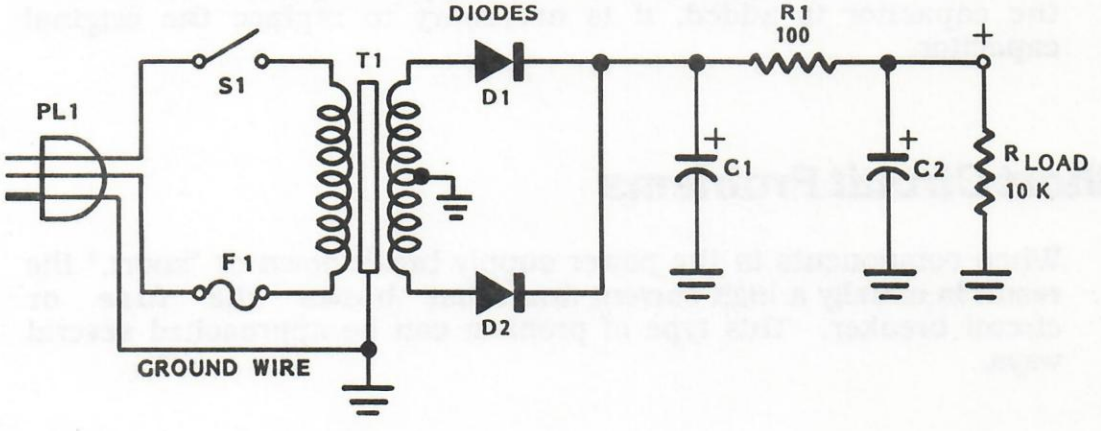


Figure 6 - Typical full-wave power supply.

Ripple Problems

It is possible for the dc output level of the power supply to be normal or close to normal, but for the ripple level to be higher than normal. It is also desireable to use an oscilloscope to check the ripple frequency as well as the ripple voltage. We know from past experiments that the filter circuit, consisting primarily of capacitors, is responsible for removing ripple from the output. If the scope indicates a higher than normal ripple level, the filter capacitors would be suspect. If, however, the oscilloscope indicates a ripple frequency of 60 Hz rather than 120 Hz for the full-wave power supply in Figure 6, the capacitors may not be at fault. The fault could be an OPEN DIODE (either D1 or D2) causing half-wave rectification instead of full-wave rectification. The increased ripple level exists because the filter circuit components were designed to filter the output of a full-wave circuit and are not adequate for filtering a half-wave circuit. A test of the two diodes, D1 and D2 of Figure 6, using the techniques shown earlier in Figures 3 and 4, will quickly indicate which diode is open. Another less frequent fault that will produce the same symptoms is when half of the centertapped secondary winding on T1 opens. This has the same effect as an open diode.

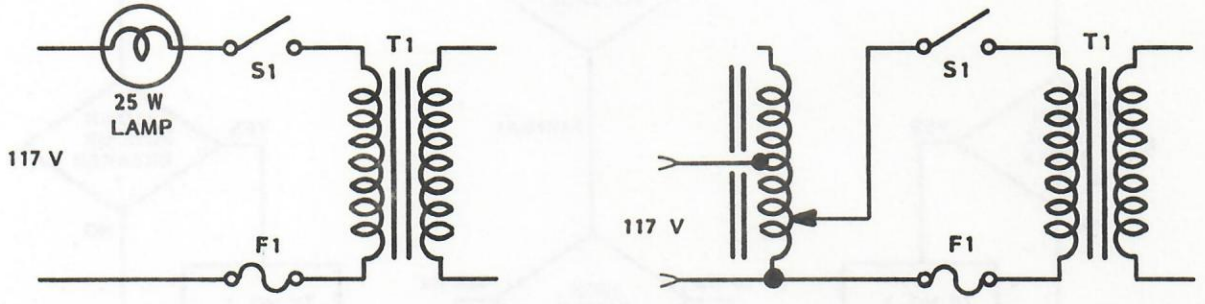
Because of the heat generated in a power supply, the electrolytic capacitors will often dry out, thus losing capacitance. This, of course, results in a higher than normal ripple level but with a normal ripple frequency of 120 Hz. This clue, a 120 Hz ripple, indicates that the capacitors should be checked rather than the diodes or transformer. The check is simple; parallel the filter capacitors with a test capacitor that is close in value and observe the effect on the ripple level. If the ripple drops to normal when the capacitor is added, it is necessary to replace the original capacitor.

Short Circuit Problems

When components in the power supply break down or "short," the result is usually a high current drain that blows the fuse or circuit breaker. This type of problem can be approached several ways.

1. Test for the short using an ohmmeter with the power supply unplugged from the power line.

2. Insert a 25 watt lamp in series with the ac power line as shown in Figure 7(a) and perform voltage tests at the reduced input voltage level. This will produce lower than normal readings but permit voltage tests without blowing the fuse.



(a) SERIES LAMP (b) VARIAC CONTROL

Figure 7 - Two methods of reducing the input voltage to a power supply to prevent the fuse from blowing.

3. Use a Variac, an adjustable autotransformer (Figure 7(b)), to reduce the ac input to the power supply so that the fuse doesn't blow and proceed with voltage measurements.

Employing one of the above steps will allow testing without burning out fuses or any major components.

Troubleshooting Procedure

The flow chart in Figure 8 presents a logical series of steps to locate a fault in a power supply. Each result requires that one of the eight test procedures be followed to enable you to find the specific component at fault.

8 - DIODE TESTING AND TROUBLESHOOTING

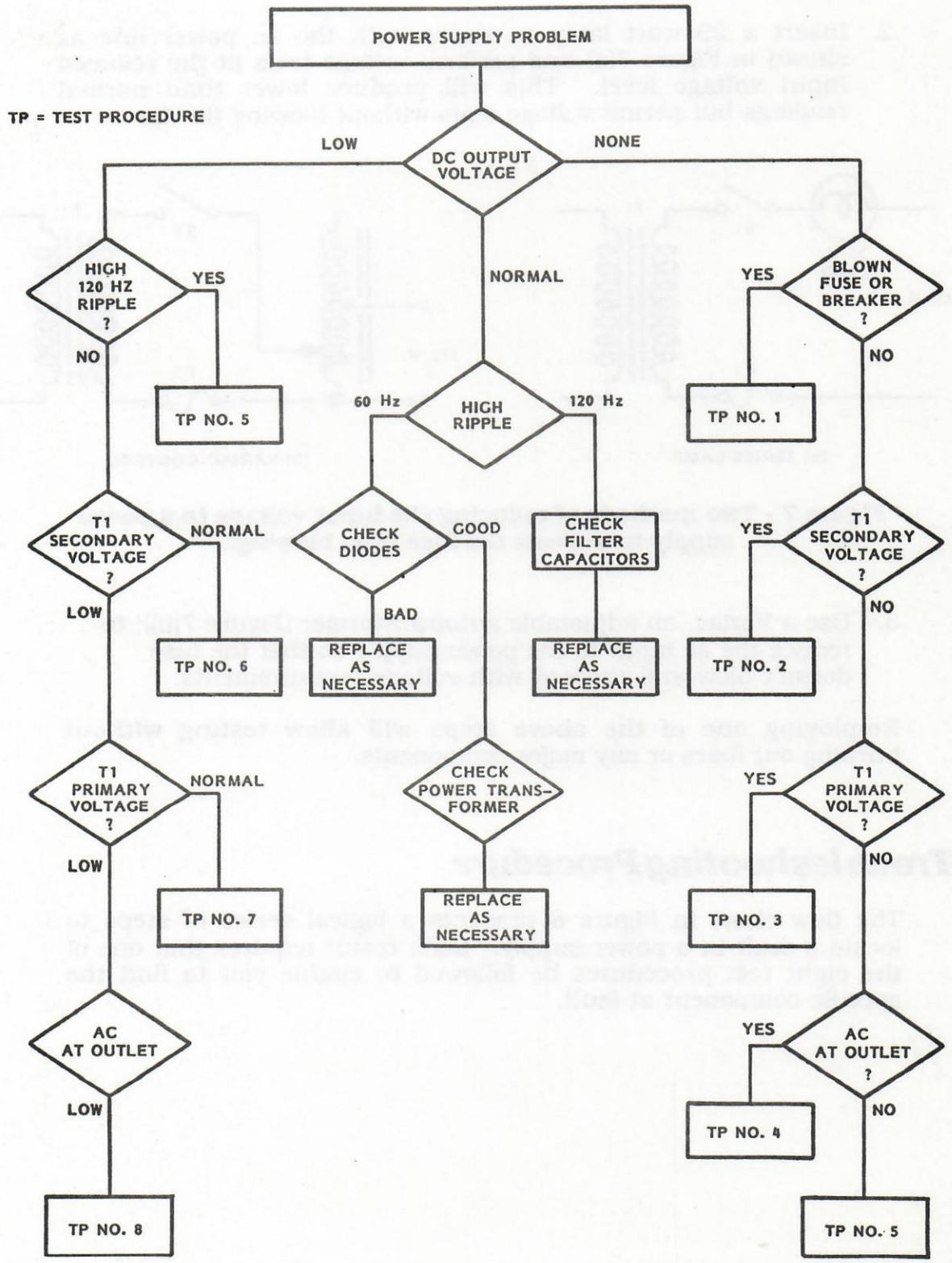


Figure 8 - Power supply troubleshooting flow chart.

TEST PROCEDURE NO. 1

A blown fuse is caused by a:

- Short in the load
- Shorted filter capacitor, C1 or C2
- Shorted diode, D1 or D2
- Shorted turns in a T1 winding

TEST PROCEDURE NO. 2

If the fuse does not blow and the T1 secondary voltage is normal, check the diodes for open circuit.

TEST PROCEDURE NO. 3

If there is no secondary voltage and the primary voltage is normal, test for an open primary or secondary winding or a break in the wiring on the PC card.

TEST PROCEDURE NO. 4

If there is no primary voltage and the outlet is hot, check for:

- An open ON-OFF switch
- Open line cord or plug
- Blown fuse that *appears* good but has no continuity.

TEST PROCEDURE NO. 5

If there is no ac at the outlet, check the power line circuit breaker. Try another outlet.

TEST PROCEDURE NO. 6

If the ripple is high and 120 Hz, in addition to a low dc level, some possible faults are:

- An open input filter capacitor
- A filter capacitor that has greatly reduce capacitance
- Excessive current loading caused by a partial short in a filter capacitor
- Excessive current drain by the load due to a short.

TEST PROCEDURE NO. 7

If the secondary voltage is low and the primary voltage is normal, check the transformer, T1.

TEST PROCEDURE NO. 8

If the ac outlet voltage is low, there is a power line problem. Try another power line circuit, if possible. Check the power line circuit breaker.

Conclusions

We have learned from this information sheet that:

1. The most frequently used diode case is the cylindrical form.
2. The color band on the diode case identifies the cathode.
3. Diodes may be testing using an analog ohmmeter, a digital VOM that has a DIODE TEST position and a dc voltage source and a voltmeter.
4. A diode that reads a low resistance in one direction and infinity in the other direction is a good diode.
5. A diode is shorted if it reads low in both directions.
6. A diode is open if it reads high in both directions.
7. An open diode in a full-wave rectifier circuit will change the ripple frequency from 120 Hz to 60 Hz and increase the ripple level.
8. A shorted diode will overload the power transformer and burn out the fuse.
9. An open filter capacitor will cause an increase in the ripple voltage but may or may not reduce the dc level.
10. An excessive current load on the power supply will lower the dc output voltage and raise the level of ripple.
11. When a power supply burns out fuses constantly, it is possible to make voltage measurements to locate the fault if you first reduce the input ac voltage using a Variac or place a 25 watt bulb in series with the primary.
12. It is possible to locate a fault in a power supply by following the troubleshooting procedure as outlined in the flow chart.

Key Terms

1. FILTER CIRCUIT

   A combination of L, C and R components used to remove the ac component from the output of a rectifier circuit.

2. RIPPLE VOLTAGE

   The varying portion of the dc output voltage of a power supply. It may be measured using an oscilloscope or ac meter.

3. RIPPLE FREQUENCY

   The frequency of the ac ripple voltage present in the output of a power supply. The ripple frequency is determined by the power line frequency and the type of rectification, half or full-wave.

4. TEST CAPACITOR

   A capacitor with two test leads attached that may be used to parallel a capacitor that is believed to be open.

5. TEST PROCEDURE

   A testing procedure, when troubleshooting, that is based on an understanding of the circuit operation and follows a logical series of steps.

Assignment

Answer the following multiple choice questions.

1. A normal diode, when tested with an analog ohmmeter, will read _____in one direction and _____in the reverse direction. _____

   a) high; high
   b) low; low
   c) low; high
   d) medium resistance; high

2. A shorted diode, when tested with an analog ohmmeter, will read _____ in one direction and _____in the reverse direction. _____

   a) high; high
   b) low; low
   c) low; high
   d) high; low

3. An open diode, when tested with an analog ohmmeter, will read _____ in one direction and _____ in the reverse direction. _____

   a) high; high
   b) low; low
   c) low; high
   d) high; low

4. A normal diode, when tested using a digital ohmmeter, will read _____ in one direction and _____ in the reverse direction. _____

   a) high; high
   b) low; low
   c) low; high
   d) high; low

5. A diode measures 50 ohms forward resistance and 1 megohm reverse resistance. The diode is: _____

   a) shorted
   b) open
   c) silicon
   d) germanium

6. Components used in the power supply are subject to frequent failure because they are: _____

   a) subjected to very low currents.
   b) are too inexpensive and they always break down.
   c) subjected to high currents and a lot of heat.
   d) none of the above.

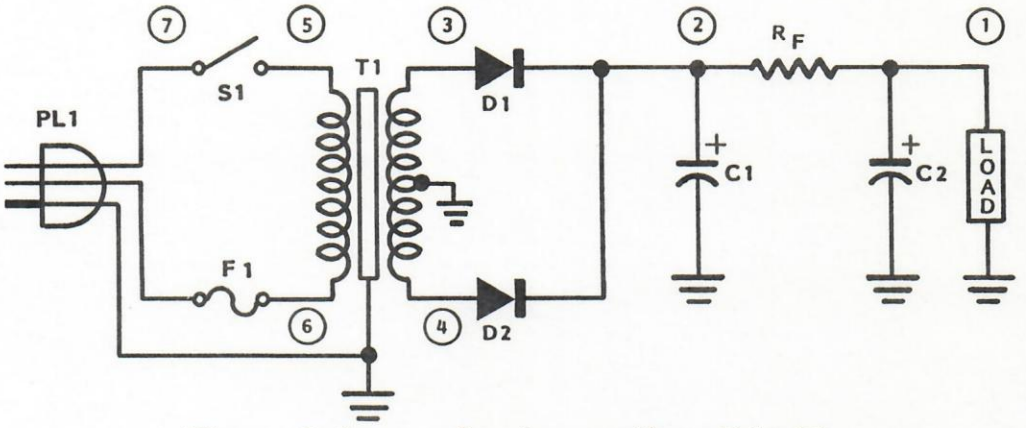


Figure 9 above refers to questions 7 to 11.

7. In the circuit of Figure 9, the fuse (F1) burns out each time S1 is turned on. Diodes D1 and D2 have been disconnected from points 3 and 4. The most probable cause is: _____

   a) a defective fuse.
   b) a shorted switch.
   c) shorted turns on T1.
   d) all of the above.

8. In the circuit of Figure 9, a check at point 1 with an oscilloscope indicates a normal level of dc, a higher than normal ripple level and a ripple frequency equal to the line frequency. The most likely cause is: _____

   a) an open filter capacitor.
   b) an open diode, D1 or D2.
   c) both D1 and D2 are open.
   d) C2 shorted.

9. There is no ac voltage measured between 3 and 4 in Figure 9. The possible cause is an open: _____

   a) switch, S1
   b) line cord
   c) primary winding
   d) all of the above

10. The dc output voltage at point 1 in Figure 9 is lower than normal and resistor RF is overheating. The most likely cause is a(an): _____

    a) leaky capacitor, C2
    b) open resistor, RF
    c) break in the load
    d) none of the above

11. In Figure 9, no voltage appears from point 3 to ground but the normal ac appears from 4 to ground. _____

    a) This is normal.
    b) Half of the T1 secondary is open.
    c) T1 primary winding is defective.
    d) Diode D1 is open.

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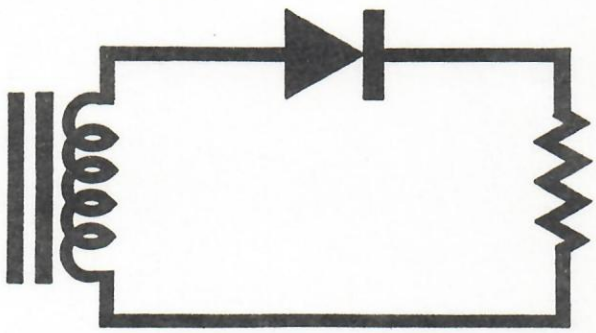

H1

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DIODES and POWER SUPPLIES
PART H1

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ISBN 0-86711-175-5
Printed in the United States of America

CES INDUSTRIES, INC.
Educational Products Division
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Farmingdale, New York 11735
Phone (516) 293-1420

PART H1 - DIODES and POWER SUPPLIES

Table of Contents

EXPERIMENTS

1. Diode Characteristic Curve Plot
2. Diode Characteristic Oscilloscope Display
3. Half-wave Rectifier Circuit Operation
4. Full-wave Rectifier Circuit Operation
5. Filter Circuit Operation
6. Diode Peak Repetitive and Surge Currents
7. Voltage Multiplier Circuit Operation
8. Power Supply Troubleshooting.

Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part E1 and G1. Review this lesson.

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Lab Manual
DIODES and POWER SUPPLIES
PART H1

Diode Characteristic Curve Plot 1

Objectives

When you have finished this experiment, you will be able to:

1. Plot the characteristics of a diode using the point-by-point method.
2. Measure the necessary data and calculate the bulk resistance of a diode.
3. Measure the leakage current of a diode.
4. Determine the barrier potential of the germanium and silicon diodes.

Additional Equipment Required

1 - Digital VOM

Reference

Information Sheet 1, Solid State PN Junctions

Procedure

1.1 Point-By-Point Silicon Diode Plot

In this part of the experiment we will plot the forward and reverse characteristics of a silicon diode using the point-by-point method.

2 - DIODE CHARACTERISTIC CURVE PLOT

1. Wire the circuit shown in Figure 1.

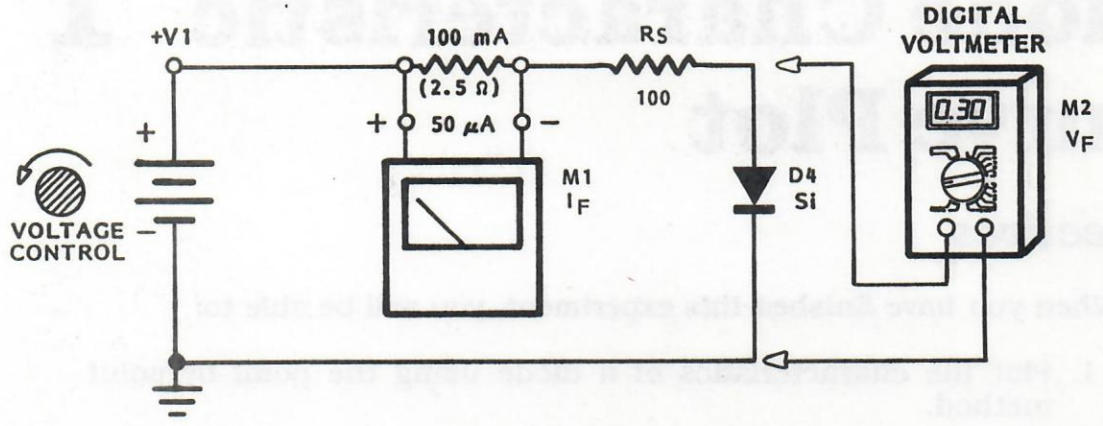


Figure 1- Si diode forward characteristic curve EXPERIMENT.

2. Starting from zero volts (voltage control fully ccw), slowly rotate the control to obtain each of the forward voltage drops listed in Table 1. Record the current flow for each forward voltage.

VF	IF	VF	IF
0	0	0.55*	
0.1		0.6*	
0.2		0.65	
0.3*		0.7	
0.4*		0.75	
0.5*		0.8	

* To read the very low currents for these forward voltages, disconnect one end of the 2.5 ohm shunt resistor to obtain a reduced current range of 50 microamperes.

TABLE 1- Silicon diode forward voltage *versus* current.

3. Reverse the polarity of the Si diode in order to measure its leakage current.

Remove the 2.5 ohm shunt resistor for a full-scale range of 50 μA.

Silicon Diode Leakage Current, I_L = _____ .

The leakage current of a silicon diode is very low (less than a nanoampere) and thus and should not be readable on a 0 to 50 microampere meter.

4. Plot the data from Table 1 on the graph of Figure 2.

   Mark off and label the three areas of the diode curve; 1- OFF, 2- KNEE, and 3- LINEAR.

   Extend the linear portion of the plot until it intersects the forward voltage axis. This extension indicates the diode's barrier potential, VB. Record VB in the space provided.

   VB Si = _____

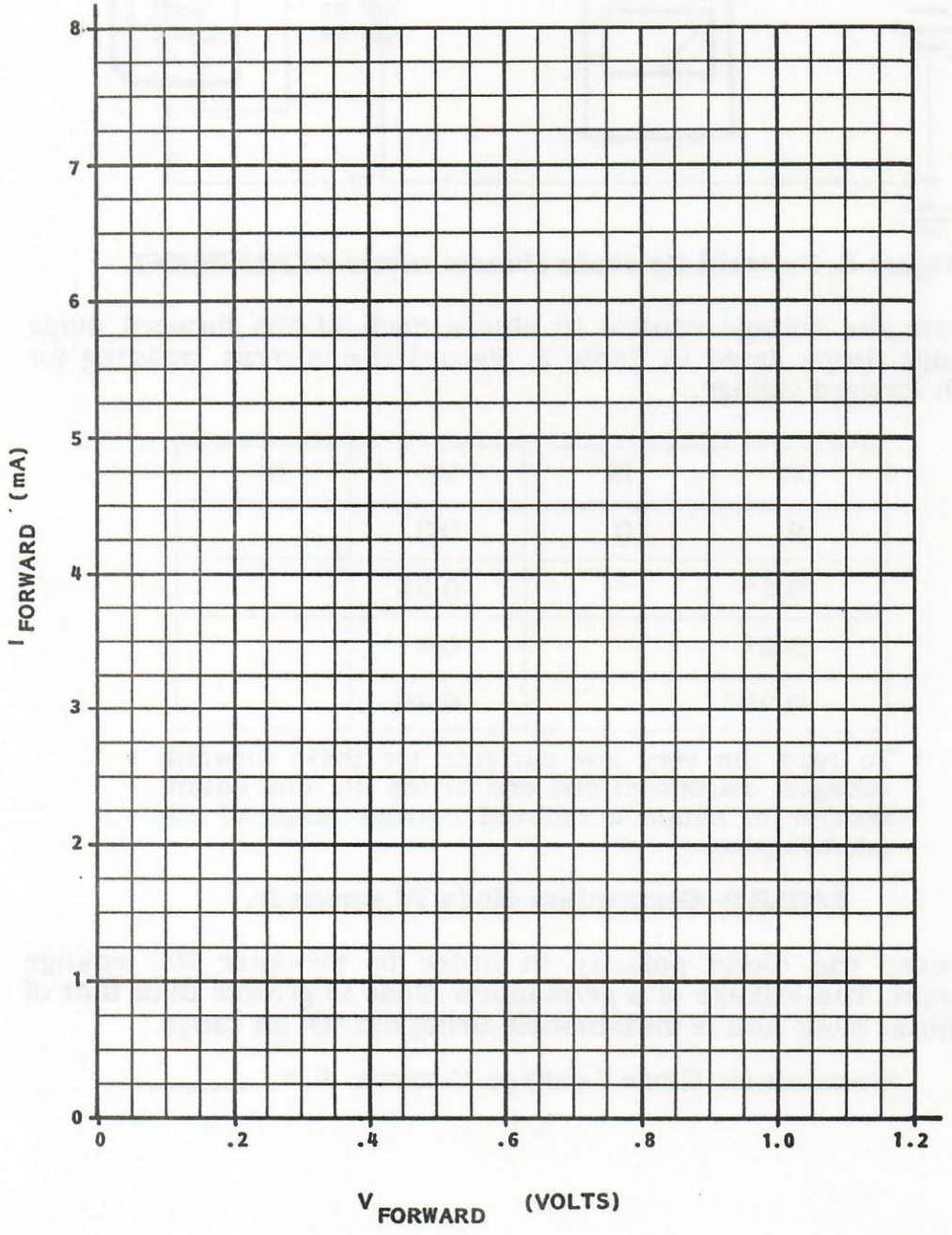


Figure 2- Silicon diode forward voltage - current characteristics.

1.2 Point-By-Point Germanium Diode Plot

5. Wire the circuit shown in Figure 3. Note that the value of Rs, the milliammeter shunt, and the diode have been changed.

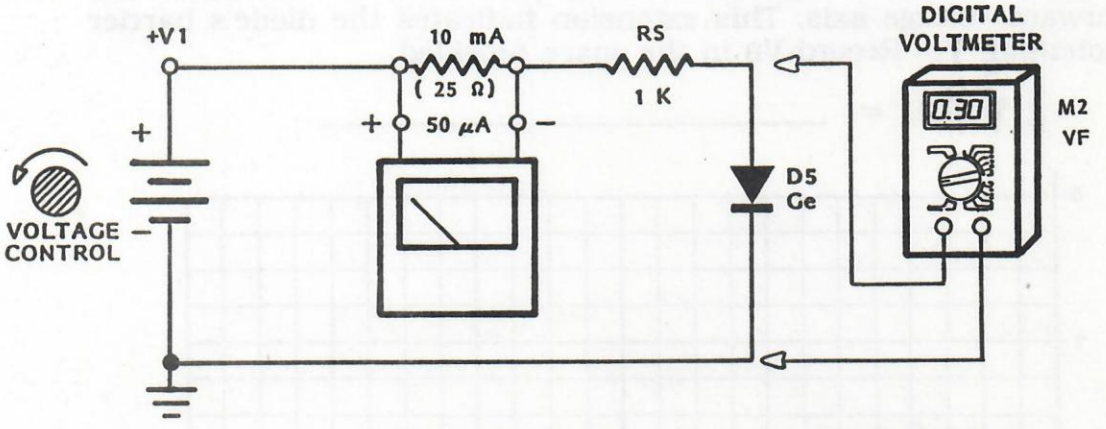


Figure 3- Forward Ge diode characteristic EXPERIMENT.

6. Rotate the voltage control to obtain each of the forward diode voltage drops listed in Table 2. Record the current reading for each forward voltage.

VF	IF	VF	IF
0	0	0.3	
0.1*		0.35	
0.2*		0.4	
0.25*		0.45	

* To read the very low currents for these forward voltages, disconnect one end of the 25 ohm shunt resistor to obtain a reduced current range of 50 microamperes.

TABLE 2- Germanium diode VF versus IF.

7. Reverse the diode polarity in order to measure its leakage current. The leakage of a germanium diode is greater than that of a silicon diode and is measureable using the 50 μA range.

Germanium Diode Leakage Current, I_L = _____.

8. Plot the data from Table 2 on the graph of Figure 4.

   Mark off and label the three areas of the diode curve; 1- OFF, 2- KNEE, 3- LINEAR.

   Extend the linear portion of the plot until it intersects the forward voltage axis to determine the diode's barrier potential, VB.

   VB Ge = _____

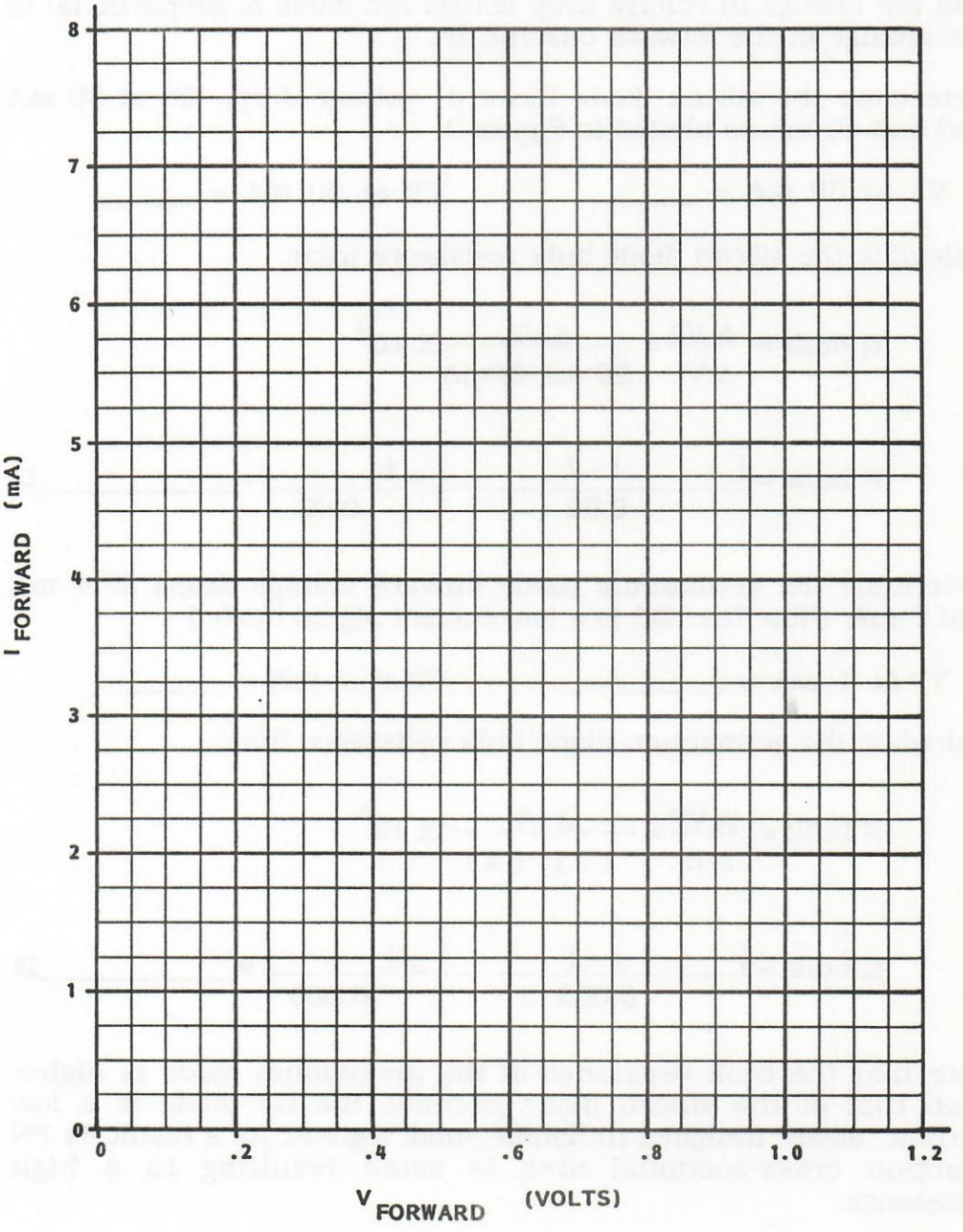


Figure 4 - Germanium diode forward voltage - current characteristics.

Do the measured barrier voltages for the Si and Ge diodes agree with the theoretical values of 0.7 and 0.3 volts given earlier in Information Sheet 1? _____

1.3 Diode Bulk Resistance

In this part of the experiment, we will calculate the bulk resistance, RB, of the Si and Ge diodes using the data recorded on the graphs of Figures 2 and 4. Once the diode is conducting past the knee of the characteristic curve, the diode acts as a resistance and the change in voltage drop across the diode is proportional to the change in the forward current, IF.

9. Determine the silicon diode forward voltage drop, VF, at 30 mA and and 50 mA as plotted in Figure 2.

   VF at 30 mA = _____ VF at 50 mA = _____

10. Calculate the silicon diode bulk resistance from:

$$R_{bulk} = \frac{\Delta V_F}{\Delta V_I} = \frac{\Delta V_F}{50\text{ mA} - 30\text{mA}} \times 10^3$$

$$R_{bulk} = \frac{(\quad) - (\quad)}{0.02} = \frac{(\quad)}{0.02} = \_\_\_\_\_\ \Omega$$

11. Determine the germanium diode forward voltage drops at 4 mA and 7 mA. (Note that D5 is a low current signal diode.)

    VF at 4 mA = _____ VF at 7 mA = _____

12. Calculate the germanium diode bulk resistance from:

$$R_{bulk} = \frac{\Delta V_F}{\Delta I_F} = \frac{\Delta V_F}{(7) - (4)} \times 10^3$$

$$R_{bulk} = \frac{(\quad) - (\quad)}{0.003} = \frac{(\quad)}{0.003} = \_\_\_\_\_\ \Omega$$

Note that the bulk resistance of the germanium diode is higher than that of the silicon diode because the Ge diode is a low current device designed to handle small signals. As a result its PN junction cross-sectional area is small resulting in a high resistance.

Conclusions

We have learned from this experiment that:

1. The silicon diode is used for high current circuits.
2. The germanium diode is used for low current signal circuits.
3. Silicon diodes have very low reverse leakage currents.
4. Silicon diodes have a low bulk resistance due to a large PN junction cross-sectional area that allows them to carry high currents.
5. Germanium diodes have greater reverse leakage currents and have a small PN junction cross-sectional area which results in a greater bulk resistance.

Assignment

Answer the following multiple choice questions.

1. The approximate forward voltage drops across silicon and germanium diodes are _____ and _____, respectively. _____

   a) 0.7 V ; 0.3 V
   b) 0.3 V ; 0.3 V
   c) 0.3 V ; 0.7 V
   d) 0.7 V ; 0.7 V

2. When choosing a diode that will produce minimum leakage, the best choice would be one made from: _____

   a) germanuim.
   b) silicon.
   c) indium.
   d) any of the above.

3. Exceeding the piv rating of a diode will cause the diode to: _____

   a) stop conducting.
   b) increase IF.
   c) avalanche.
   d) none of the above.

4. When forward biased, a diode presents a _____ resistance and when reverse biased, _____ resistance. _____

   a) high ; low
   b) high ; high
   c) low ; medium
   d) low ; high

5. Draw the circuit of a diode wired across a dc voltage source so that it is forward biased.

Draw arrows indicating the direction of electron flow in the circuit drawn.

Diode Characteristic Oscilloscope Display 2

Objectives

When you have finished this experiment you will be able to:

1. Display the characteristic curves of a silicon and germanium diode on an oscilloscope screen.
2. Measure the reverse voltage across the diode.
3. Observe the effect of the diode's reverse recovery time on diode performance.

Reference

Information Sheet 1, Solid State PN Junctions

Procedure

2.1 Silicon Diode Curve Display

In this part of the experiment we will set up the oscilloscope for X-Y operation to enable us to display the forward and reverse diode characteristics on the screen.

1. Wire the circuit shown in Figure 1.

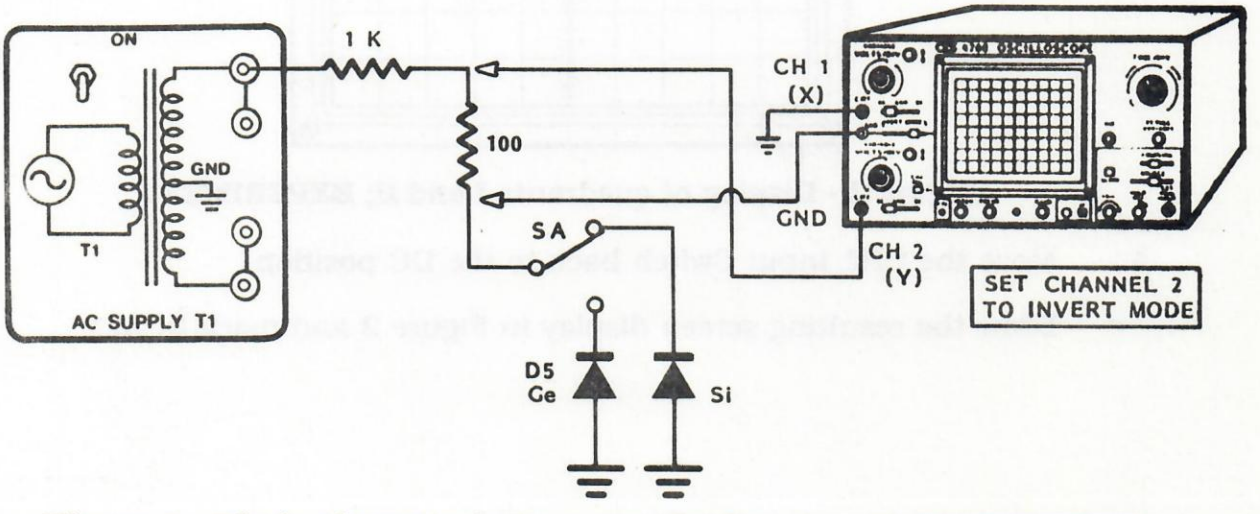


Figure 1 - Diode characteristic curve display circuit; EXPERIMENT.

2. Set the oscilloscope controls as follows:

CH1 V/DIV	0.2	CH1 Input Sw	DC
CH2 V/DIV	0.2	CH2 Input Sw	DC
CH2 Invert	Depress	TIME/DIV	X-Y

Place all VARIABLE controls in the CAL position.

3. Set switch SA UP to connect the silicon diode into the circuit.

Apply power to the oscilloscope and trainer and the diode curve will appear on the screen. Because there are no data in quadrants III and IV, only quadrants I and II will be displayed using the procedure that follows.

a. Set the CH1 Input Switch to the GND position.

b. Adjust the X Position control so that the vertical trace is centered from left to right.

c. Adjust the Y Position control so that the vertical trace starts from the bottom of the screen.

The above procedure will result in the display of quadrants I and II as shown in Figure 2.

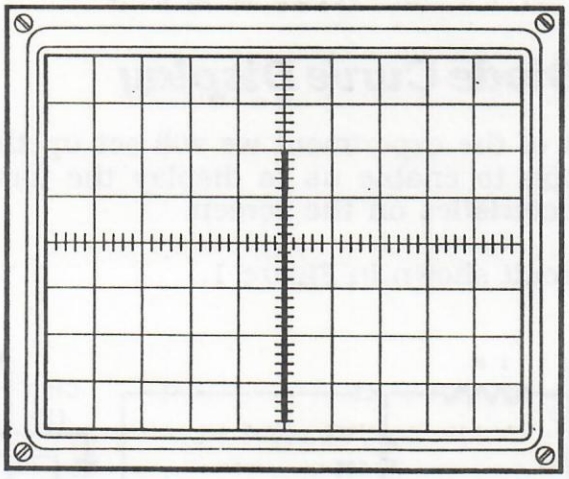
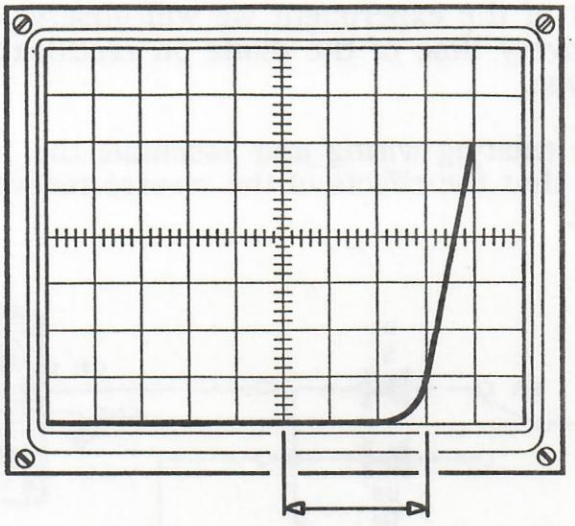


Figure 2 - Display of quadrants I and II; EXPERIMENT.

4. Move the CH1 Input Switch back to the DC position.

Draw the resulting screen display in Figure 2 and mark it "Si."

5. Determine V_B, the barrier potential of the diode, from the screen display as shown below.



V_B Si = (V/DIV) (No. of Div.)

V_B Si = (0.2) ( ) = _____

How close is the measured forward voltage to 0.7 volts?_____

2.2 Germanium Diode Curve Display

6. Set switch SA DOWN to connect the germanium diode into the circuit.

   Draw the new trace that appears on the oscilloscope screen onto the graph in Figure 2 and label it "Ge."

7. Determine V_B, the barrier potential, for the germanium diode from the screen display.

   V_B Ge = _____

   How close is the measured forward voltage to 0.3 volts? _____

2.3 Diode Reverse Recovery Time (trr)

In this part of the experiment we will observe the effect of the reverse recovery time of the diode on rectification for both the Si and Ge type.

8. Remove the existing wiring and assemble the circuit shown in Figure 3 so that the effects of the reverse recovery time (trr) can be observed.

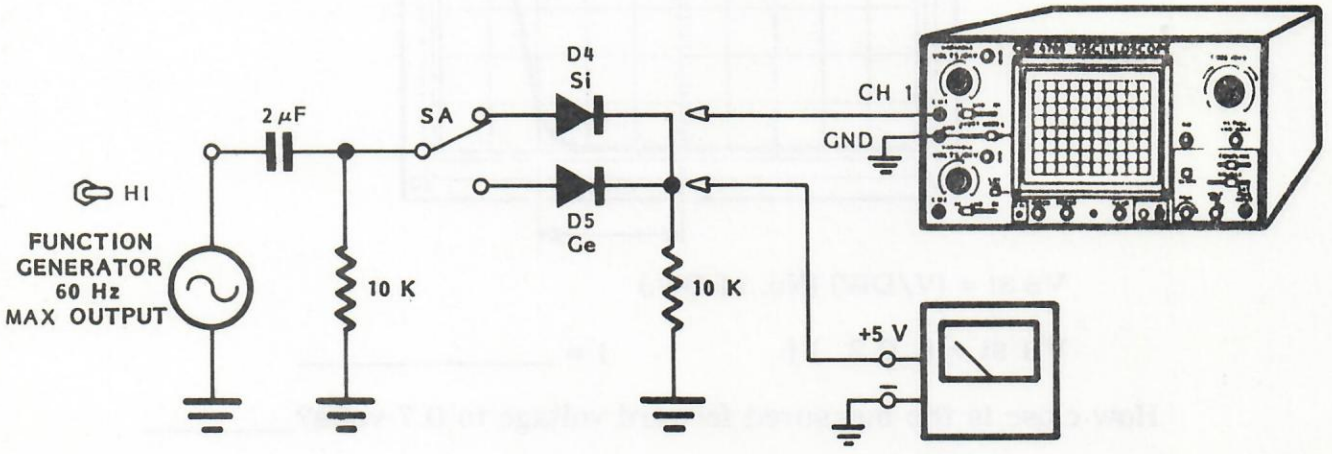


Figure 3 - Reverse recovery time EXPERIMENT.

9. Set the Function Generator for a 60 Hz sine wave at full output.

Set the oscilloscope controls as follows:

CH1 V/DIV	2	TIME/DIV	5mS
VERT MODE	CH1	SOURCE	CH1
CH1 INPUT SW	DC		

10. Set switch SA UP for the silicon diode, D4.

The oscilloscope display will be the positive half of the ac input cycle. The negative half of the cycle is blocked when it reverse biases the diode. The average dc voltage is registered on the panel meter.

11. Move switch SA UP and DOWN, observing both the waveforms and the dc output voltages for the Si and Ge diodes. Draw the waveforms in the proper columns in Table 1 and enter the voltage readings in their respective columns. Note that the output voltage reading for the Ge diode is slightly higher than that for the Si diode due to the lower diode junction drop (approximately 0.3 volts).

12. Advance the Function Generator to 100 Hz, reset the scope TIME/DIV control to 2 mS and record the output waveforms and voltages in Table 1, for both diodes.

f (Hz)	TIME/DIV	OUTPUT WAVEFORMS		Vout Si	Vout Ge
		Si	Ge		
60	2 mS				
100	2 mS				
200	1 mS				
400	0.5 mS				
1 kHz	0.1 mS				
5 kHz	20 µS				
10 kHz	10 µS				
50 kHz	5 µS				
100 kHz	2 µS				

TABLE 1 - Diode output waveforms and dc output voltages versus input frequency.

13. Repeat this procedure for each frequency listed in Table 1 and note the change in the output waveform when using the silicon diode, starting approximately at 1 kHz. The change is due to the longer reverse recovery time of the high current silicon diode as compared to the low current germanium diode.

Observe that at 100 kHz, a large part of the negative half of the input cycle appears at the output when the silicon diode is in the circuit and note also the drop in dc output voltage as the frequency is increased. Observe that the circuit operation, that is , the output waveforms and the dc voltages, remain relatively unchanged for the germanium diode.

Why is the dc output voltage greater for germanium diode at the lower frequencies, typically 60 Hz? _____

_____

Based on the results of Table 1, up to what frequency does the Si diode still operate well as a rectifier? _____

_____

Conclusions

We have learned from this experiment that:

1. The diode characteristic curve can be plotted point-by-point or displayed on an oscilloscope screen using X-Y operation.

2. As the frequency at which the diode operates is increased, the diode's reverse recovery time becomes more of a problem.

3. Small signal diodes have a smaller junction area and thus a shorter reverse recovery time. This results in a higher permissible operating frequency.

Assignment

Answer the following questions.

1. The reverse recovery time of a diode is important because it determines the; _____

   a) maximum piv of the diode.
   b) highest allowable forward current.
   c) highest allowable ac operating frequency.
   d) all of the above.

2. A diode that has a PN junction with a large cross-sectional area will have a: _____

   a) low current carrying capability.
   b) good high frequency response.
   c) poor high frequency response.
   d) low piv rating.

3. A silicon diode has a barrier potential of _____ and a germanium diode has a barrier potential of _____. _____

   a) 0.7 V; 0.3 V
   b) 0.3 V; 0.7 V
   c) 0.7 V; 0.7 V
   d) 0.3 V; 0.3 V

4. Match the right hand column of answers to the left column.

_____ I_F	a) Reverse diode voltage drop
_____ V_R	b) Forward diode voltage drop
_____ piv	c) Reverse diode leakage
_____ trr	d) Forward diode current
_____ I_R	e) Peak diode reverse voltage
_____ V_F	f) Reverse diode recovery time

Half-Wave Rectifier Circuit Operation 3

Objectives

When you have finished this experiment you will be able to:

1. Wire a half-wave rectifier circuit.
2. Calculate and measure the dc output voltages for the half-wave rectifier circuit.
3. Display the AC input, DC output and diode waveforms for the half-wave rectifier circuit.

Reference

Information Sheet 2, Rectifier Circuits

Procedure

3.1 Half-Wave Rectifier Circuit

In this part of the experiment we will wire a half-wave rectifier, measure the ac input voltage to the rectifier and then calculate the theoretical expected dc output voltage. We will then measure the actual dc output voltage and compare it to the theoretical expected value.

1. Wire the half-wave rectifier circuit shown in Figure 1.

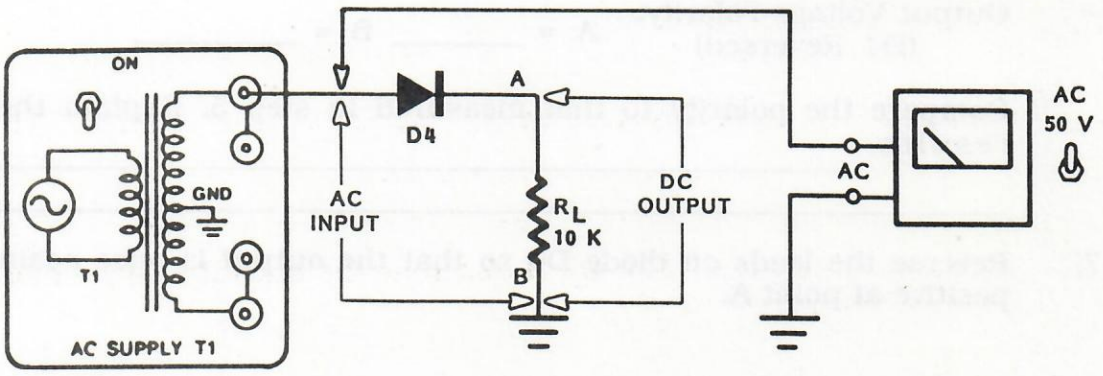


Figure 1 - Half-wave rectifier; EXPERIMENT.

2. Measure the ac input voltage using the panel meter on the 50 volt ac range and record the value in the space provided.

   AC Input Voltage to Rectifier = _____

3. Calculate the expected average dc output voltage that will appear across RL in Figure 1 using the following equation:

   Theoretical Vdc = (v ac in) (0.45) =

   Theoretical Vdc = ( ) (0.45) = _____V

4. Measure the actual dc output voltage across RL and record the value below.

   DC Output Voltage = _____V

   Compare the measured dc output to the theoretical dc output voltage calculated in step 3. How close are the two voltages?

   _____

3.2 Rectifier Output Voltage Polarity

In this part of the experiment we will observe the effect on the output voltage polarity when the rectifier diode polarity is reversed.

5. Measure the dc output voltage across RL in Figure 1 and record the polarity of points A and B.

   Output Voltage Polarity: A = _____ B = _____

6. Reverse the polarity of diode D4 in Figure 1.

   Measure the dc output voltage across RL and record the polarity of points A and B.

   Output Voltage Polarity:
   (D4 Reversed) A = _____ B = _____

   Compare the polarity to that measured in step 5. Explain the results.

   _____

   _____

7. Reverse the leads on diode D4 so that the output is once again positive at point A.

3.3 Half-Wave Rectifier Circuit Waveforms

In this part of the experiment we will observe the waveforms that appear in the half-wave rectifier circuit, measure the piv that appears across the diode and measure the peak dc output voltage.

8. Connect a dual trace oscilloscope to the half-wave rectifier circuit as shown in Figure 2.

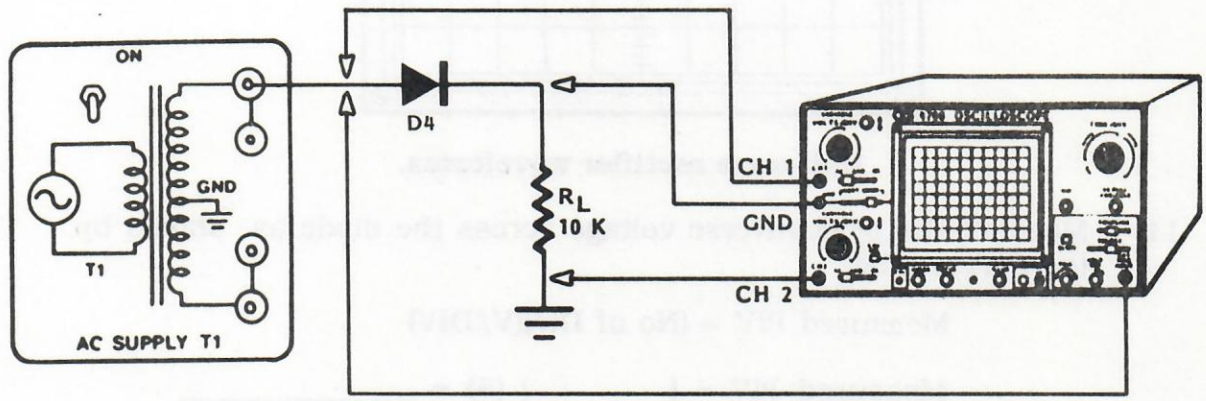


Figure 2 - Waveform observation EXPERIMENT.

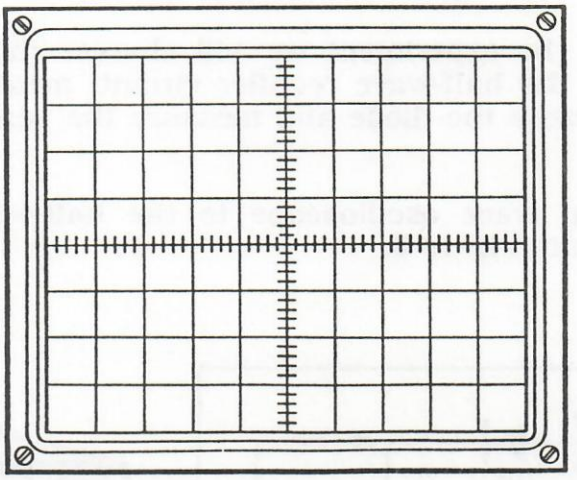
9. Adjust the oscilloscope controls as follows:

CH 1 V/DIV	5	CH 2 INV	Depressed
CH 2 V/DIV	5	TIME/DIV	2 mS
CH 1 INPUT SW	DC	SYNC SOURCE	EXT
CH 2 INPUT SW	DC	VERT MODE	CHOP

Be certain that all VARIABLE controls are in the CAL position.

10. Adjust the centering controls so that the diode waveform (CH 1) is at the top of the screen and the dc output voltage (CH 2) is at the bottom of the screen.

Record the circuit waveforms displayed on the oscilloscope, in the space provided below.



Half-wave rectifier waveforms.

11. Measure the peak inverse voltage across the diode as shown by the CH1 display.

    Measured PIV = (No of Div)(V/DIV)

    Measured PIV = ( ) (5) = _____

12. Calculate the theoretical expected piv from:

    Theoretical PIV = (v in) (1.414)

    Theoretical PIV = ( ) (1.414) = _____

    Compare the measured piv to the calculated piv above. How close are they?

    _____

13. Measure the peak dc output voltage across RL as indicated by the CH2 display.

    Measured Peak dc Output = (No of Div) (V/DIV)

    Measured Peak dc Output = ( ) (5) = _____

14. Calculate the theoretical peak dc output voltage from:

    Theoretical Peak dc Output = (v ac in) (1.414)

    Theoretical Peak dc Output = ( ) (1.414) = _____

    How do the theoretical and measured peak output voltages compare?

    _____

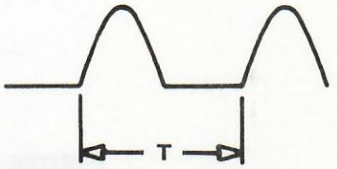
3.4 Half-Wave Ripple Frequency

In this part of the experiment we will measure the frequency of the ripple voltage, the ac component of the rectifier output. The ripple frequency will be equal to the power line frequency which is normally 60 Hz in most areas.

15. Measure the time base for one cycle of the output as shown below and calculate the ripple frequency.

f = 1/T = 1/ [(No. Div) (Time/Div)]

f = 1/ [( ) ( )] = _____



If your oscilloscope is accurately calibrated and you read the divisions accurately, the time base will be 16.67 mS for a ripple frequency of 60 Hz.

Conclusions

We have learned from this experiment that:

1. The average dc output voltage for a half-wave rectifier, operating into a resistive load, is equal to the rms input voltage multiplied by 0.45.

2. The peak inverse voltage that appears across the diode in the half-wave rectifier is equal to the rms input voltage multiplied the rms input voltage multiplied by 1.414.

3. The ripple frequency in the dc output of a half-wave rectifier is equal to the power line frequency.

Assignment

Answer the following multiple choice questions.

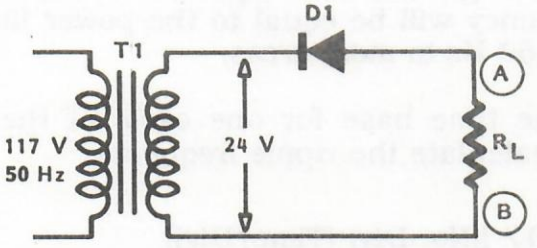


Figure 4 above refers to questions 1 to 10.

1. For the circuit shown in Figure 4, the average dc voltage across RL will be closest to: _____

   a) 24 V.
   b) 12 V.
   c) 10.8 V.
   d) 6.3 V.

2. The peak voltage across RL in Figure 4 will be closest to: _____

   a) 36.9 V.
   b) 33.9 V.
   c) 24 V.
   d) 10.8 V.

3. The piv that will appear across D1 in Figure 4 will be closest to: _____

   a) 36.9 V.
   b) 33.9 V.
   c) 24.0 V.
   d) 21.6 V.

4. The ripple frequency of the output in Figure 4 will be: _____

   a.) 100 Hz.
   b) 60 Hz.
   c) 50 Hz.
   d) 30 Hz.

5. The polarity of the dc output across RL in Figure 4 will be: _____

   a) A+, B-
   b) A-, B+
   c) changing at a 60 Hz rate.
   d) changing at a 50 Hz rate.

6. Given a period of 20 milliseconds for a complete output cycle for the half-wave rectifier circuit of Figure 4, the ripple and line frequencies, in that order, are: _____

a) 120 Hz and 60 Hz.
b) 100 Hz and 50 Hz.
c) 50 Hz and 50 Hz.
d) 60 Hz and 50 Hz.

7. The small voltage difference that will be found between the peak input to the rectifier and the peak dc output, in the circuit of Figure 4, can be attributed to: _____

a) diode voltage drop.
b) a power line input voltage greater than 117 V.
c) unknown causes.
d) peak voltage loss in RL.

8. The T1 secondary voltage in Figure 4 is fed to CH 1 of the oscilloscope. Given a 10 V/DIV control setting, the trace will cover: _____

a) 1.2 cm.
b) 2.4 cm.
c) 3.39 cm.
d) 6.78 cm.

9. The output polarity of the circuit of Figure 4 may be reversed by reversing the: _____

a) T1 primary connections.
b) T1 secondary connections.
c) diode polarity.
d) any of the above.

10. The waveform that will appear across RL, the output of the half-wave rectifier of Figure 4, is closest to: _____

a)
c)
b)
d)

Full-Wave Rectifier Circuit Operation 4

Objectives

When you finish this experiment you will be able to:

1. Wire a full-wave rectifier circuit and bridge rectifier circuit.
2. Calculate and measure the ac input and dc output voltages for each circuit.
3. Measure the diode piv for each circuit.
4. Display the input waveforms, the output waveforms and the diode waveforms for each circuit.

Reference

Information Sheet 2, Rectifier Circuits

Procedure

4.1 Full-Wave Rectification

In this part of the experiment we will wire a full-wave rectifier circuit using two diodes (D3, D4) and the full secondary winding of transformer T1. We will then calculate and measure the dc output voltage and observe the circuit waveforms.

1. Wire the full-wave rectifier circuit shown in Figure 1.

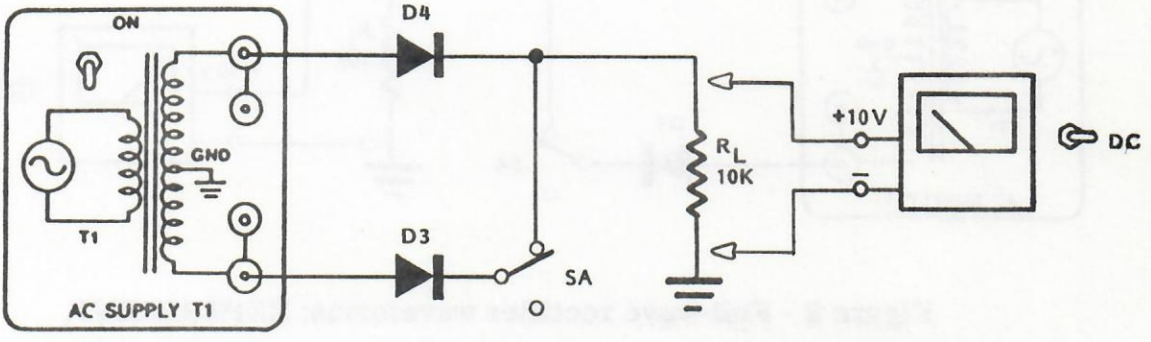


Figure 1 - Full-wave rectifier EXPERIMENT.

2. Place switch SA in the UP position for a full-wave circuit.

   Measure the ac input voltage to diode D3 and record the value below.

   AC Input Voltage to Diode D3 = _____

3. Calculate the expected average dc output voltage that will appear across RL in Figure 1 using the following equation:

   Theoretical DC Output = (υ ac in) (0.9)

   Theoretical DC Output = ( ) (0.9) = _____

4. Measure the actual dc output voltage across RL and record the value below.

   Measured DC Output Voltage = _____

   Compare the measured and calculated values of the dc output. Are they close in value?

   _____

4.2 Full-Wave Circuit Waveforms

In this part of the experiment we will observe the input and output waveforms and compare them to half-wave operation.

5. Connect the oscilloscope to the full-wave rectifier circuit as shown in Figure 2.

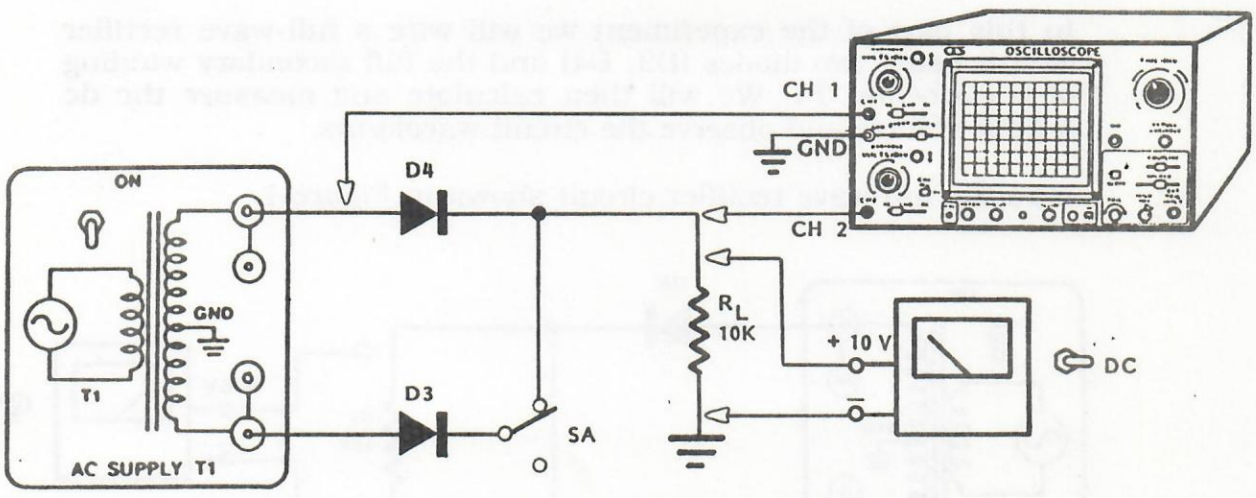
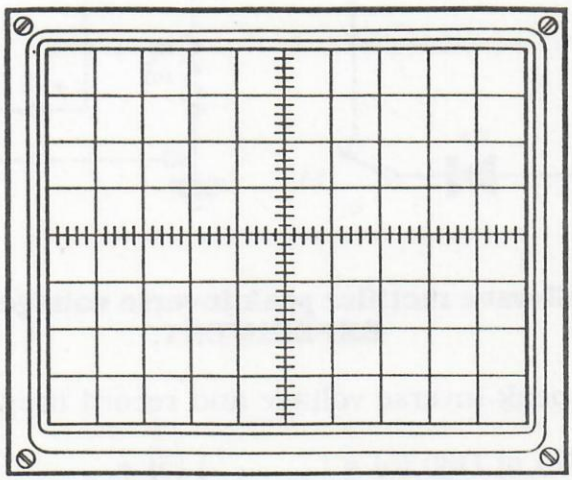


Figure 2 - Full-wave rectifier waveforms; EXPERIMENT.

Set the Sync Source switch to LINE and the TIME/DIV switch to 2 mS.

Adjust the oscilloscope so that the CH1 waveform is at the top of the screen and the CH2 waveform at the bottom of the screen.

6. Draw the input and output waveforms in the space provided.



7. Observe that full-wave operation produces *two* output pulses for each input cycle.

Place switch SA DOWN for half-wave operation and describe the change in the output waveform and the dc level. _____

_____

_____

Set switch SA back to the UP position for full-wave operation.

4.3 Peak Inverse Voltage

In this part of the experiment we will calculate the expected piv across the diodes and then measure the piv. We will then compare the peak inverse voltages for the full and half-wave rectifier circuits.

8. Connect the oscilloscope to the full wave rectifier as in Figure 3.

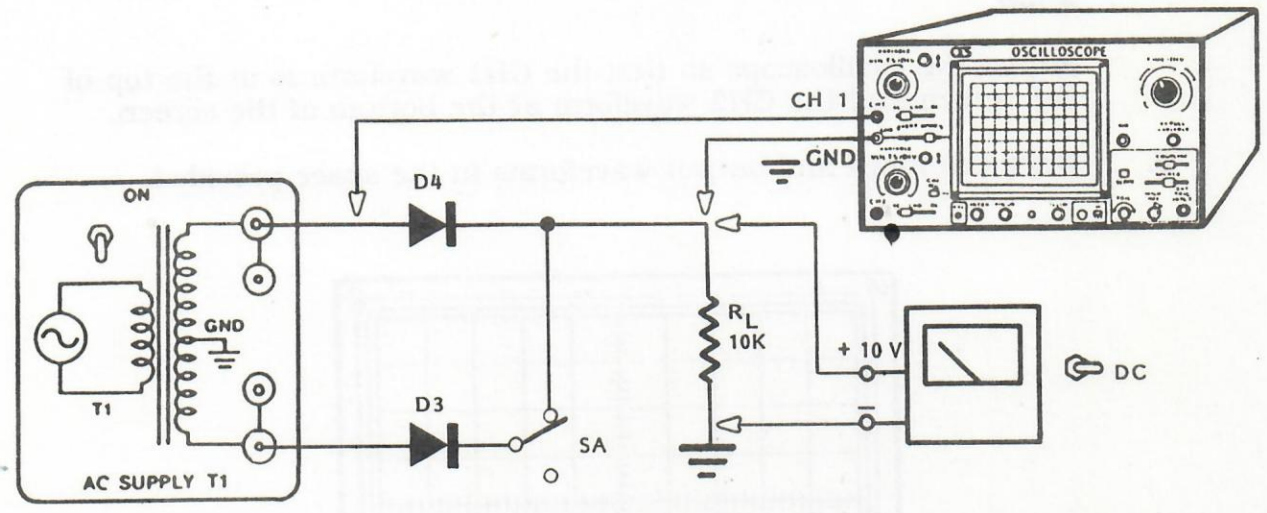


Figure 3 - Full-wave rectifier peak inverse voltage measurement; EXPERIMENT.

9. Measure the peak inverse voltage and record the value below.

   PIV = (No of Div) (5) = ( ) (5) = _____

10. Recall that the piv for the half-wave rectifier in the previous experiment was *half* this value.

    Verify this by placing switch SA in the DOWN position for half-wave operation. Measure and record the reduced piv below.

    PIV, Half-Wave Operation = _____

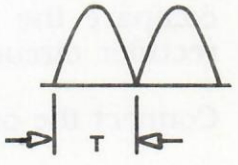
    We can conclude that the piv that appears across each diode in full-wave operation is double that for half-wave.

4.4 Full-Wave Ripple Frequency

11. Measure the time base for one pulse of the output as shown below and calculate the ripple frequency. (Be certain that switch SA is UP.)

    f = 1 / T = 1 / ( )

    F-W Ripple Frequency = _____



Compare the full-wave ripple frequency to that generated by the half-wave rectifier. _____

_____

4.5 Bridge Rectifiers

In this part of the experiment we will wire a bridge rectifier circuit in which a secondary center-tap is not needed. The dc output voltage of this bridge rectifier is twice that obtained from the half and full-wave rectifiers only because we are using the full transformer secondary with twice the windings. When a center-tap is available and grounded, as on our trainer, the bridge is actually two full-wave rectifiers, one positive with respect to ground and the other negative with respect to ground.

12. Remove the existing wiring and wire the circuit shown in Figure 4.

Because the center tap of the transformer secondary is permanently grounded, the negative terminal of the dc output voltage cannot be connected to the trainer ground. A common negative terminal is created using Tie Point B1 which is located to the right of the power transformer on the panel.

13. Calculate the expected dc output voltage from :

Vdc av = v ac in (0.9)

Recall that the ac input is the full transformer secondary voltage, 20 volts rms. Thus:

Calculated Vdc av = (20) (0.9) = _____

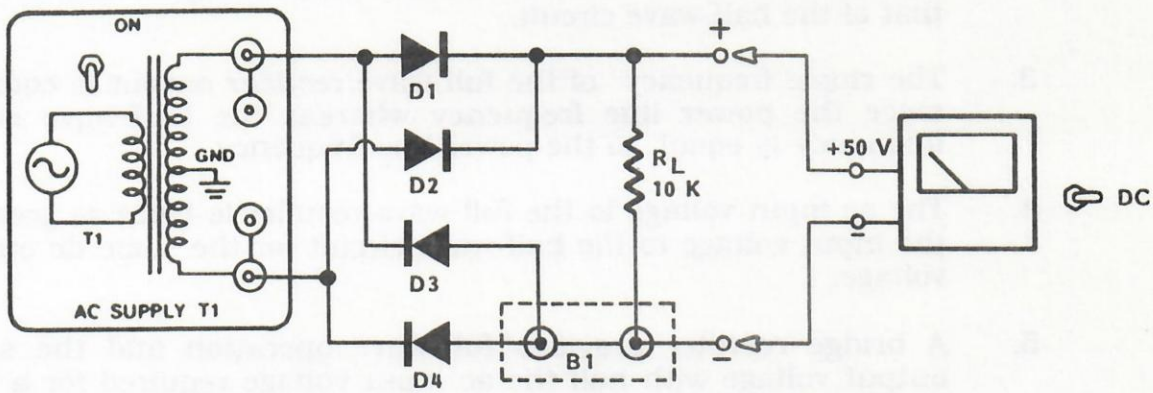


Figure 4 - Bridge rectifier circuit EXPERIMENT.

14. Measure the average dc output voltage across RL and record it below.

Measured Vdc av = _____

How close are the measured and theoretical calculated dc output voltages?

_____

15. Connect the oscilloscope across the bridge rectifier output and observe the waveform.

    Is half-wave or full-wave operation indicated by the waveform across RL?

    _____

16. Measure the peak dc output voltage indicated by the output waveform and record it below.

    Vdc pk = _____

17. Observe and measure the piv across each of the rectifier diodes using the oscilloscope. Record the piv for each diode below.

    piv D1 _____ piv D2 _____ piv D3 _____ piv D4 _____

    Observe that the piv across each diode in the bridge rectifier is equal to the peak voltage of the full transformer secondary (20 x 1.414 = 28.28 V).

Conclusions

We have learned from this experiment that:

1. For a full-wave rectifier operating into a resistive load, the expected average dc output voltage is found from (*v*rms) (0.9) as compared to (*v* rms) (0.45) for the half-wave rectifier.

2. The piv that appears across each diode in a full-wave rectifier is equal to the peak ac of the full secondary voltage which is *twice* that of the half-wave circuit.

3. The ripple frequency of the full-wave rectifier output is equal to twice the power line frequency whereas the half-wave ripple frequency is *equal* to the power line frequency..

4. The ac input voltage to the full-wave rectifier is twice as great as the input voltage to the half-wave circuit for the same dc output voltage.

5. A bridge rectifier provides full-wave operation and the same output voltage with half the ac input voltage required for a full-wave rectifier circuit. When the full secondary voltage is used the bridge will produce twice the dc output.

6. The piv across each of the four diodes in the bridge rectifier is equal to the peak secondary voltage just as in the full-wave rectifier.

7. The ripple frequency of the bridge rectifier circuit output is equal to twice the power line frequency.

Assignment

Answer the following multiple choice questions.

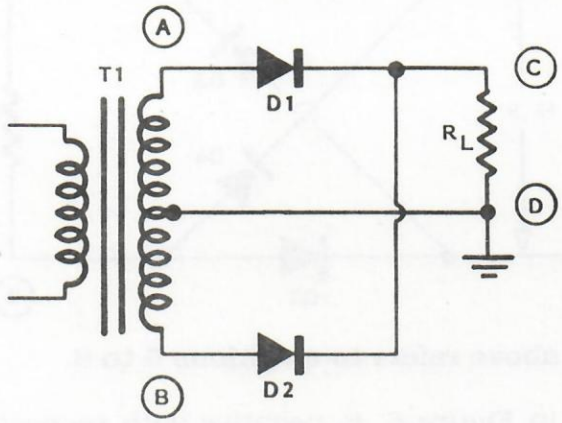


Figure 5 above refers to questions 1 to 4.

1. The secondary voltages on T1, from A to the center tap and B to the center tap, in Figure 5, are: _____

   a) equal in amplitude and in phase.
   b) equal in amplitude but 180 degrees out of phase.
   c) unequal in value (B greater than A) and out of phase.
   d) unequal in value (A greater than B) and in phase.

2. The waveform that appears across RL in Figure 5 is closest to: _____

   a)
   c)
   b)
   d)

3. The ripple frequency for the circuit of Figure 5 is equal to: _____

   a) the line frequency.
   b) half the line frequency.
   c) twice the line frequency
   d) none of the above.

4. Given a full secondary voltage of 24 volts in Figure 5, the average dc across RL will be: _____

   a) 33.9 V.
   b) 17 V.
   c) 12 V.
   d) 10.8 V.

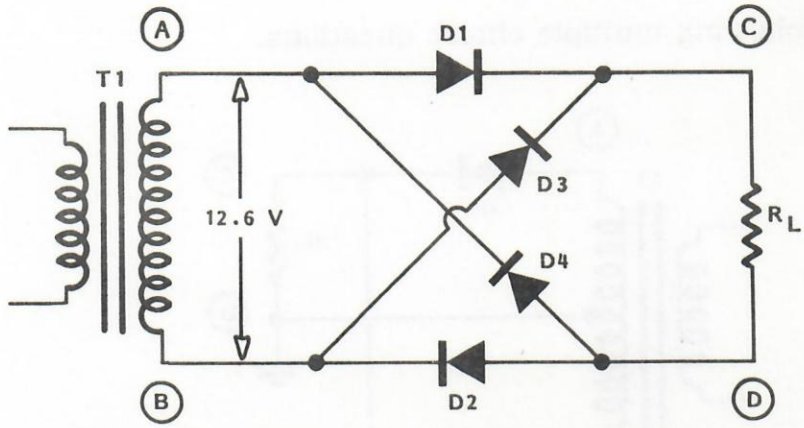


Figure 6 above refers to questions 5 to 8.

5. When point A, in Figure 6, is negative with respect to B on T1, the conducting diodes are: _____

   a) D3 and D4.
   b) D1 and D2.
   c) D1 and D4.
   d) D3 and D1.

6. When measuring the average dc across RL in Figure 6, a meter will read approximately: _____

   a) 12.6 V.
   b) 11.3 V.
   c) 10.0 V.
   d) 5.67 V.

7. When powered by a 60 Hz line, the output ripple frequency in Figure 6 will be: _____

   a) 30 Hz.
   b) 60 Hz.
   c) 120 Hz.
   d) none of the above.

8. The waveform that appears across RL of Figure 6, is: _____

   a)
   c)
   b)
   d)

9. The advantage of the bridge rectifier compared to the full wave rectifier is that it: _____

   a) requires half the ac input for the same dc output.
   b) requires twice the ac input for the same dc output.
   c) has a higher ripple frequency.
   d) has a lower ripple frequency.

Filter Circuit Operation 5

Objectives

When you finish this experiment you will be able to:

1. Observe the effect on the output voltage and the piv when a filter capacitor is added to a half-wave rectifier.
2. Measure the change in ripple voltage level when filtering is added to the rectifier output.
3. Observe and measure the improvement in the ripple percentage when the rectifier is changed from half-wave to full-wave operation.

Reference

Information Sheet 3, Power Supply Filters

Procedure

1. Wire the unfiltered half-wave rectifier shown in Figure 1.

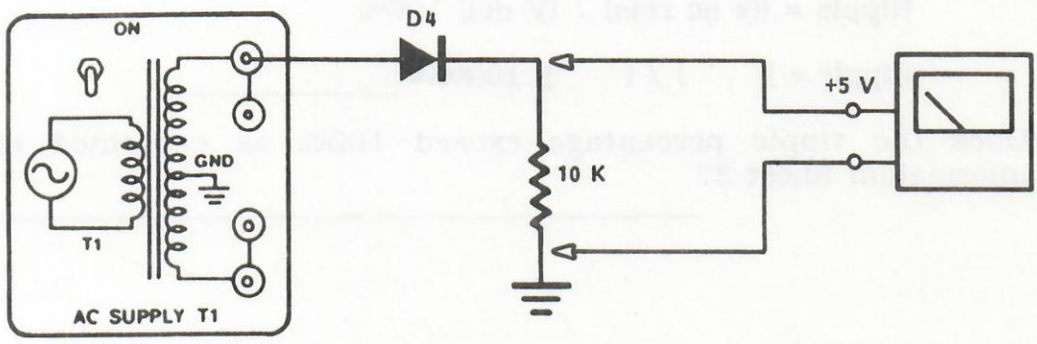


Figure 1 - Unfiltered half-wave rectifier EXPERIMENT.

5.1 Half-Wave Output Voltages

In this part of the experiment we will measure the dc output voltage and ripple output voltage of a half-wave (HW) unfiltered rectifier circuit and calculate the ripple level as measured in percentage.

2. Measure the average dc output voltage as indicated on the panel meter and record the reading below.

   Unfiltered HW DC Output Voltage = _____

3. Rewire the panel meter to read ac on the 5 volt range. Measure the output ripple voltage as shown in Figure 2 and record it below.

   Unfiltered HW AC Output Voltage = _____

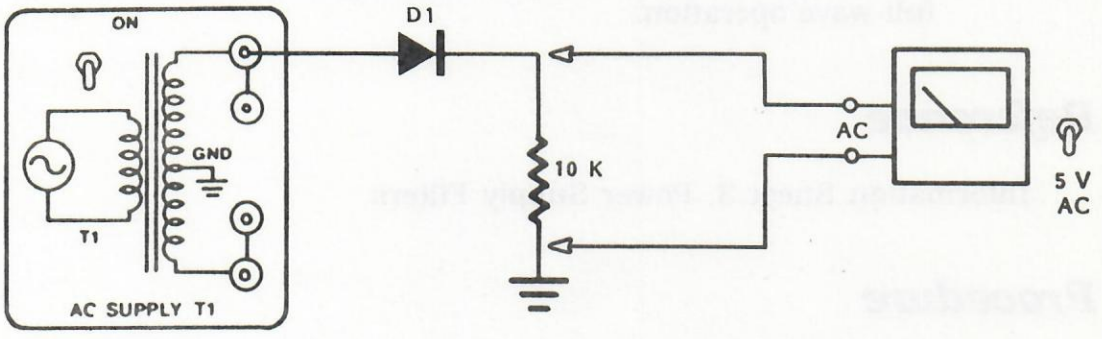


Figure 2 - Measuring the ac output level; EXPERIMENT.

4. Calculate the ripple percentage of the unfiltered circuit from:

   Ripple = [(v ac rms) / (V dc)] 100%

   Ripple = [( ) / ( )] 100% = _____

   Does the ripple percentage exceed 100% as explained in Information Sheet 3?

   _____

5.2 Peak Inverse Voltage

In this brief step of the experiment we will simply measure and record the diode piv before a filter capacitor is added to the circuit.

5. Connect the oscilloscope across the diode to measure the piv as shown in Figure 3.

6. Measure the peak inverse voltage from the display and record it below.

HW PIV Without Filter = _____

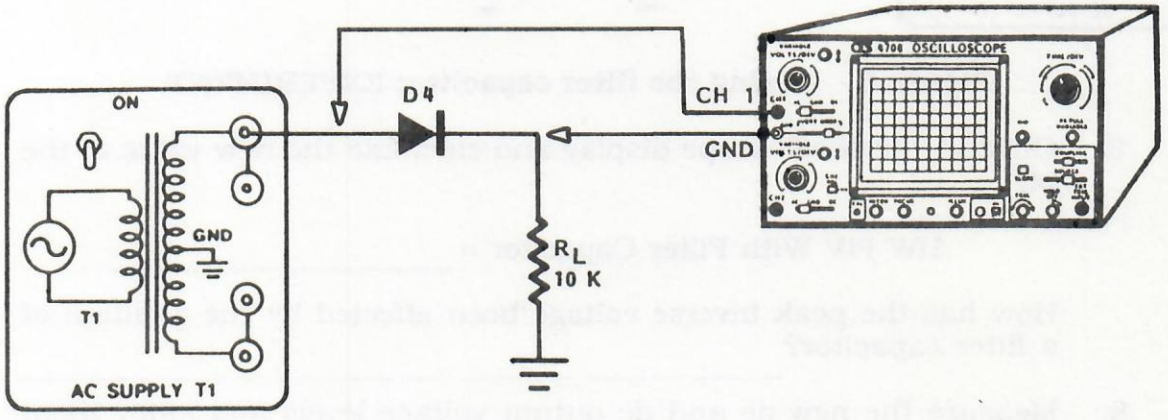


Figure 3 - Piv measurement; EXPERIMENT.

5.3 Adding a Filter Capacitor

In this part of the experiment, we will add a 10 μF filter capacitor across the dc output of the power supply and observe the effect this has upon the diode piv, the average dc output and the ripple. You will then increase the filter from 10 μF to 100 μF and compare the ripple levels for each filter.

7. Connect a 10 μF electrolytic capacitor across RL as in Figure 4. Set the meter switch to dc and use the 50 volt range.

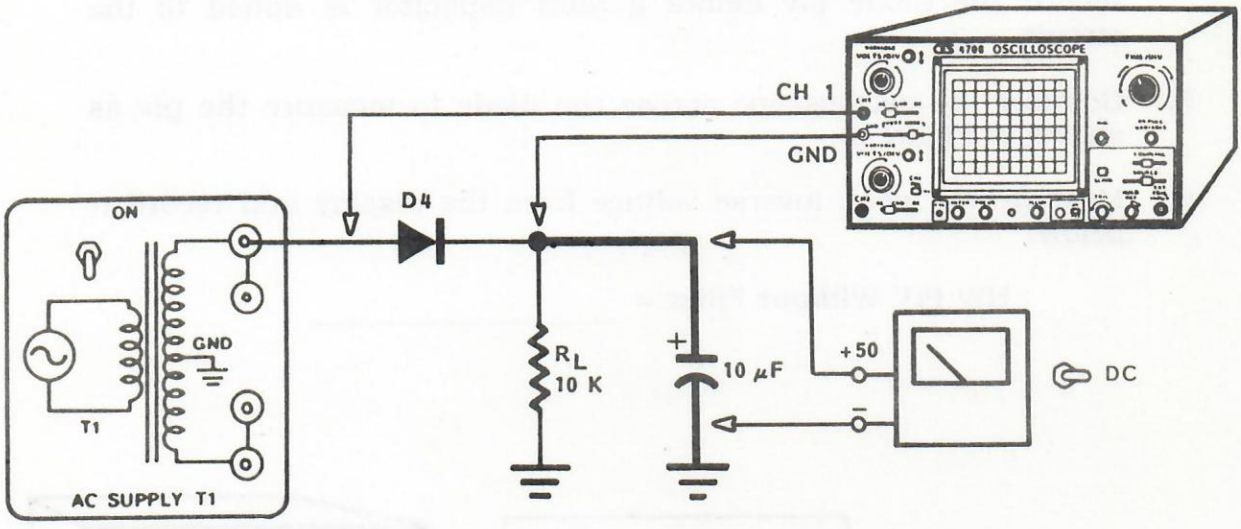


Figure 4 - Adding the filter capacitor; EXPERIMENT.

8. Observe the oscilloscope display and calculate the new value of the piv.

   HW PIV With Filter Capacitor = _____

   How has the peak inverse voltage been affected by the addition of a filter capacitor? _____

9. Measure the new ac and dc output voltage levels and enter them below.

   Output Voltages With 10 μF Filter:

   υ out rms = _____ Vout DC = _____

10. Calculate the ripple percentage with the 10 μF filter capacitor in the circuit.

    Ripple = [(υ ac rms) / (Vdc)] 100%

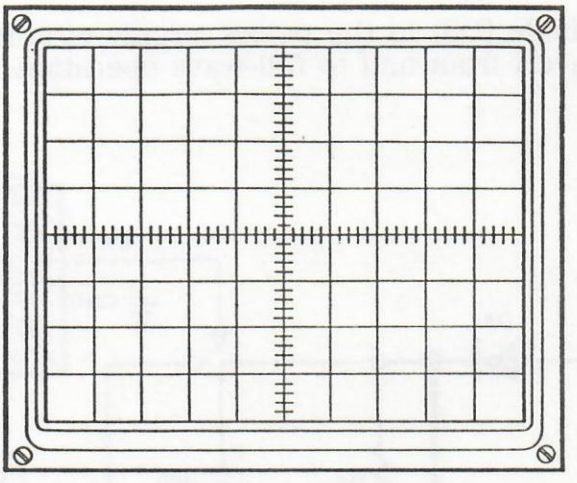
    Ripple = [( ) / ( )] 100% = _____

    How does the addition of the filter capacitor affect the ripple level in the output? _____

    _____

11. Move the oscilloscope connections to view the output waveform acrosss RL, 10 K.

    Record the output waveform and indicate the peak-to-peak ripple voltage shown on the crt screen.



P-P Ripple Voltage With 10 μF Filter = _____ υ p-p

12. Increase the value of C1 from 10 μF to 100 μF.

    Set CH1 of the oscilloscope for ac and increase the sensitivity to display the low ripple voltage. Measure the new ac and dc voltages and record them below. Use the panel meter to measure the dc output.

    Output Voltages With 100 μF Filter:

    υ out rms = _____ V out DC = _____

13. Calculate the new ripple percentage from the above measurements as shown below.

    Ripple = [(v ac rms) / (Vdc)] 100%

    Ripple = [( ) / ( )] 100% = _____

    How does increasing the value of the filter capacitor from 10 μF to 100 μF affect the level of the ripple voltage in the output of the power supply? _____

5.4 Full-Wave Operation

In this part of the experiment you will add a second diode to convert from half-wave to full-wave operation. You will then observe the effect that full-wave operation has on the dc and ac output voltages.

15. Add a second diode (D3) to the power supply circuit, as shown in Figure 5, to convert from half to full-wave operation.

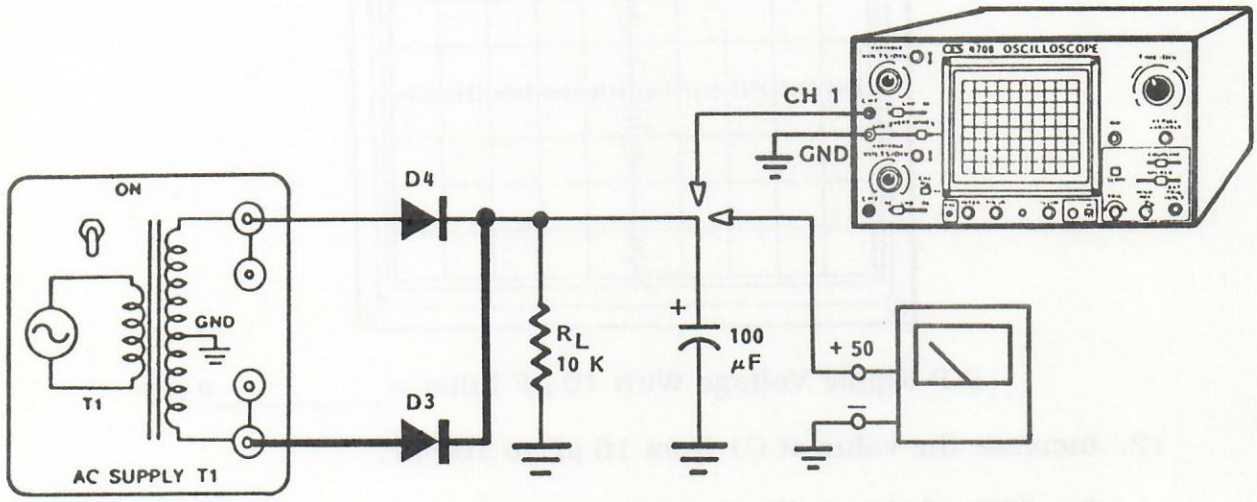


Figure 5 - Full-wave rectification; EXPERIMENT.

16. Measure the dc and ripple voltage output levels and record them below.

Output Voltages With FW Operation and a 100 μF Filter:

υ out rms = _____ Vout DC = _____

Calculate the new ripple percentage when full-wave rectification is used.

Ripple % With FW Rectification = _____

How does converting from H-W to F-W rectification affect the ripple percentage?

_____

5.5 Ripple Versus Load Current

In this part of the experiment we will increase the current drain from the power supply by reducing the value of RL and observe the effect on the ripple voltage.

17. Change the value of RL from 10K to 2.2K and observe the waveform change across RL.

    What is the effect upon the ripple voltage when the load current is increased? _____

18. Measure the new ripple voltage level.

    P-P Ripple Voltage With Increased Load = _____

Conclusions

We have learned from this experiment that:

1. In an unfiltered half-wave rectifier circuit the ripple voltage in the output is greater than the average dc resulting in a ripple percentage greater than 100%.

2. The piv across the diode for an unfiltered half-wave rectifier circuit is equal to the peak ac input to the rectifier.

3. The piv across the diode in an unfiltered half-wave rectifier circuit doubles when a filter capacitor is added to the circuit.

4. The average dc output voltage of a half-wave rectifier circuit increases when a filter capacitor is added to the circuit.

5. As the value of the filter capacitor is increased the ripple level in the output decreases.

6. Changing the rectifier circuit from half to full-wave reduces the ripple voltage while using the same filter circuit.

7. Increasing the load current (by reducing RL) increases the ripple voltage by effectively reducing the RC time constant of the filter circuit.

Assignment

Answer the following multiple choice questions.

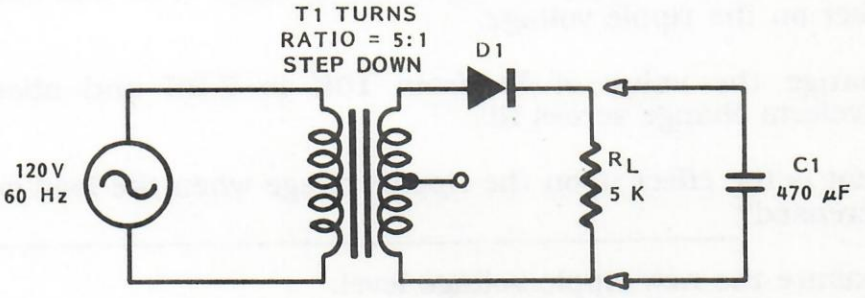


Figure 6 above refers to questions 1 to 8.

1. The dc output voltage across RL in Figure 6, without the capacitor connected, is closest to: _____

   a) 10.8 V.
   b) 21.6 V.
   c) 24 V.
   d) 33.9 V.

2. The piv across D1 in Figure 6 is closest to: _____

   a) 10.8 V.
   b) 21.6 V.
   c) 24 V.
   d) 33.9 V.

3. The average dc output voltage across RL in Figure 6, with C1 connected, is closest to: _____

   a) 10.8 V.
   b) 24 V.
   c) 34 V.
   d) 67.8 V.

4. When C1 is connected across RL in Figure 6, the piv changes to: _____

   a) 16.97 V.
   b) 24 V.
   c) 33.9 V.
   d) 67.8 V.

5. For the circuit of Figure 6, with the filter capacitor connected, the ac output voltage reads 0.5 volts rms and the dc output voltage measures 11 volts. The ripple percentage is: _____

   a) 0.045 %
   b) 4.5%
   c) 63.6%
   d) None of the above. The ripple must exceed 100% so the voltage readings must be in error.

6. Lowering the value of C1, in Figure 6, from 470 μF to 100 μF will: _____

   a) lower the ripple output slightly.
   b) raise the ripple output slightly.
   c) increase the piv.
   d) raise the average dc output voltage.

7. The circuit of Figure 6 is rewired for full-wave rectification, using two diodes and the same transformer. The new dc output voltage, with C1 connected, will be approximately: _____

   a) 10.8 V.
   b) 17 V.
   c) 19 V.
   d) 24 V.

8. Decreasing the value of RL in Figure 6 causes a (an): _____

   a) increase in load current.
   b) increase in ripple voltage.
   c) decreased dc output.
   d) all of the above.

Diode Peak Repetitive and Surge Currents 6

Objectives

When you finish this experiment you will be able to;

1. Observe and measure the diode conduction angle in a rectifier circuit.
2. Measure the peak repetitive diode current.
3. Observe and measure the diode surge current.

Reference

Information Sheet 3, Power Supply Filters

Procedure

6.1 Peak Repetitive Diode Current

In this part of the experiment we will wire a half-wave rectifier circuit, view the rectifier diode current waveform flowing through a 100 ohm resistor and observe the diode conduction angle. The conduction angle will be observed without a filter and then with a filter added.

1. Wire the circuit shown in Figure 1.

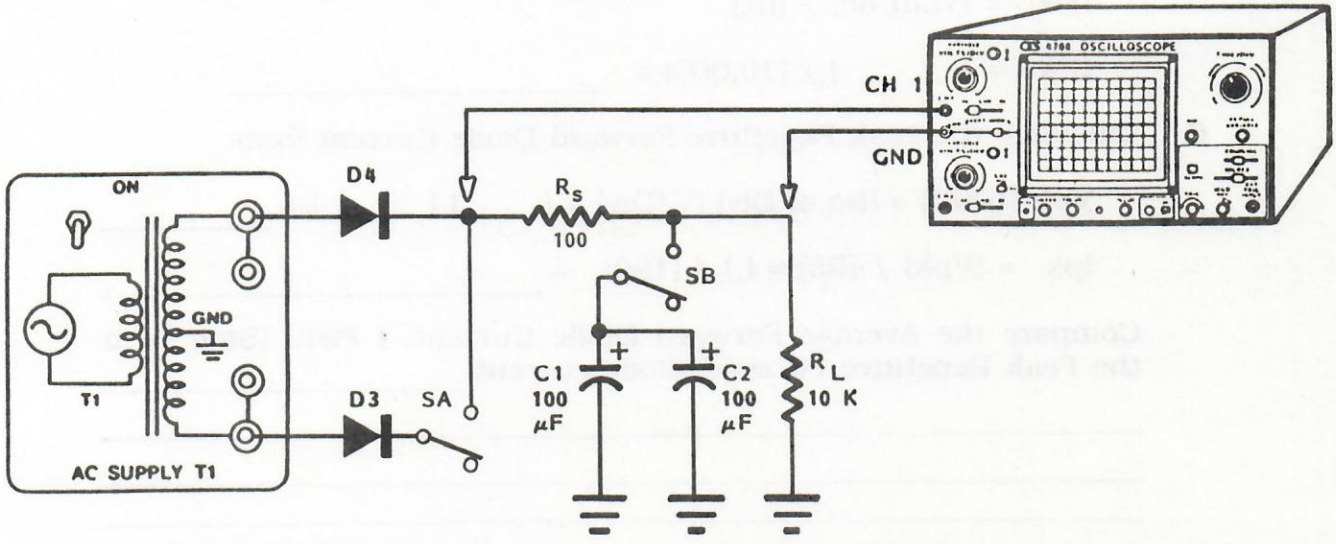


Figure 1 - Diode forward current observation; EXPERIMENT.

2 - DIODE PEAK REPETITIVE AND SURGE CURRENTS

2. Set switches SA and SB DOWN so that D3 and C1-C2 are out of the circuit.

   The forward diode current through D4 will create a voltage drop across Rs, 100 ohms, thus permitting the current waveform to be observed.

3. Connect the oscilloscope as shown and set the controls as follows:

CH 1 V/DIV	0.2V	TIME/DIV	2 mS
CH 1 INPUT/SW	DC	SYNC SOURCE	CH 1 or LINE
VERT MODE	CH 1		

   Observe that each conduction half cycle covers a full 180 degrees, 4 divisions, or 45 degrees per division when there is no filter capacitor in the circuit.

   Measure the peak current through the diode.

   Ipk = υpk/100 = ( )/(100)

   Peak Diode Current (Resistive Load) = _____

4. Add the 200 µF capacitor (C1 in parallel with C2) in parallel with RL by setting switch SB UP. Measure the effect this has on the diode conduction angle and peak current.

   Diode Conduction Angle (Capacitive Load) = _____

   Peak Diode Current (Capacitive Load) = _____

5. Calculate the average forward diode current from:

   IFWD = (Vout dc) / (RL)

   IFWD = ( ) / (10,000) = _____

6. Calculate the Peak Repetitive Forward Diode Current from:

   Vpk (100Ω) = (No of Div) (V/Div) = ( ) ( ) = _____

   Ipk = (Vpk) / (RS) = ( ) / (100) = _____

   Compare the Average Forward Diode Current, I FWD, (Step 4) to the Peak Repetitive Forward diode current. _____

   _____

   _____

   _____

6.2 Full-Wave Operation

7. Connect diode D3 into the circuit by setting switch SA UP to form a full-wave rectifier circuit.

8. Observe the changes in the peak diode current and the conduction angle as switch SA is moved UP and DOWN.

   In what way does the waveform change when the circuit is changed from half to full-wave operation?

6.3 Diode Surge Current

In this part of the experiment we will observe the surge current through the diode that occurs over the first several half cycles of conduction.

9. Make certain switch SA is UP to form a full-wave rectifier and switch SB is DOWN to remove the parallel capacitors from the circuit.

10. We will now operate the oscilloscope in the Triggered Sweep mode by setting the controls as shown below. As a result, no trace will appear until the trigger pulse arrives and the Level control setting will require adjustment for the proper display.

    Set the oscilloscope controls as follows:

CH 1 V/DIV	2	TIME/DIV	10mS
CH 1 INPUT SWITCH	DC	SYNC SOURCE	CH 1
VERT MODE	CH1	LEVEL (PULL)	NORM

    With these control settings, the waveform will appear only with a correct setting of the Trigger Level Control (close to the zero position) and SB in the UP position.

11. After setting the oscilloscope controls, proceed as follows to observe and measure the diode surge current.

    a. Set switch SB DOWN.
    b. Using a jumper wire, place a momentary short across the parallel 100 μF capacitors to discharge them and then **REMOVE** the jumper.
    c. While watching the oscilloscope screen carefully, snap Switch SB UP.

Observe that the current flow through the 100 ohm resistor is high and settles down to normal after approximately 10 half cycles of conduction.

It is necessary to discharge the capacitors each time the above procedure is followed to observe the surge current again.

12. Determine the maximum number of vertical divisions covered on the screen by the first half cycle of conduction and calculate the maximum voltage drop across R1 from:

    Vmax = (No of Div) (V/Div)

    Vmax = ( ) (2) = _____

13. Calculate the surge current on the first half cycle of conduction based on:

    Isurge = (Vrs max) / (Rs) = ( ) / (100) = _____

A surge of approximately 100 milliamperes has been obtained in a circuit where the current is limited by the resistance of the transformer secondary and series resistor of 100 ohms. If this were a transformerless circuit with no resistances and a large capacitor value, the surge current would have to be limited by a surge resistor. Note that the 10 K load only draws approximately 1 mA, but the diode must survive a surge current of 100 mA.

When selecting a diode for a power supply, all of the above ratings must be taken into account to avoid premature diode failure.

Conclusions

We have learned from this experiment that:

1. When a rectifier diode operates into a capacitive filter, the diode conducts for less than 180 degrees of the input cycle.

2. As the conduction angle of a diode is reduced, the peak diode current increases.

3. On the first several half cycles of the diode's conduction, the filter capacitor acts as a short circuit until it charges and causes a very high momentary surge of current.

4. The diode surge current must be limited to the maximum allowable value by the use of a small value resistor in series with the diode.

Assignment

Answer the following multiple choice questions.

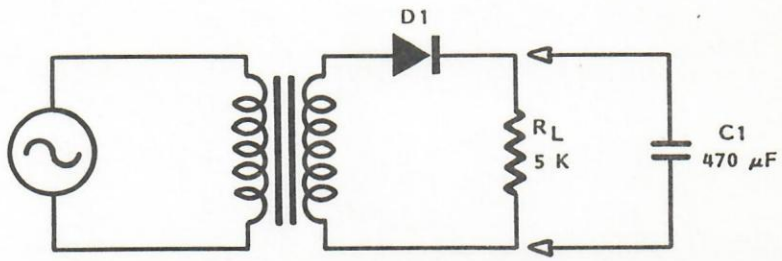


Figure 2 above refers to questions 1 and 2.

1. In the circuit of Figure 2, with C1 connected, the diode conduction angle is approximately: _____

   a) 50 degrees. c) 180 degrees.
   b) 90 degrees. d) 360 degrees.

2. In the circuit of Figure 2, with C1 disconnected, the diode conduction angle is approximately: _____

   a) 50 degrees. c) 180 degrees.
   b) 90 degrees. d) 360 degrees.

3. A half-wave power supply and full-wave power supply are both designed to deliver the same output voltage and the same load current. The peak diode current of the: _____

   a) half-wave will be highest.
   b) full-wave will be highest.
   c) half and full-wave will be the same.
   d) none of the above.

4. The surge current of a diode is caused by: _____

   a) the resistor in series with the diode.
   b) the discharge action of the filter capacitor.
   c) the charge action of the filter capacitor.
   d) all of the above.

5. The surge current rating of a diode is 30 amperes. The total circuit resistance is 0.65 ohms and the ac voltage is 120. The required series resistance is: _____

   a) 4 ohms. c) 0.75 ohms.
   b) 5 ohms. d) none of the above.

Voltage Multiplier Circuit Operation 7

Objectives

When you have completed this experiment you will be able to:

1. Wire and test the operation of a half-wave voltage doubler.
2. Wire and test the operation of a full-wave voltage doubler.
3. Wire and test the operation of a half-wave voltage tripler.
4. Wire and test the operation of a half-wave voltage quadrupler.

Reference

Information Sheet 4, Voltage Multiplier Circuits

Procedure

7.1 Full-Wave Voltage Doubler

In this part of the experiment we will wire a full-wave voltage doubler circuit, measure the dc output voltage and compare it to the ac input.

1. Wire the full-wave voltage doubler circuit shown in Figure 1.

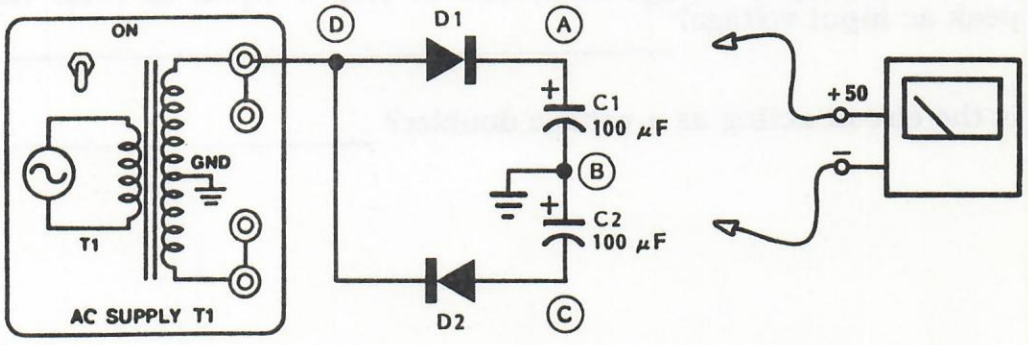


Figure 1 - Full-wave voltage doubler EXPERIMENT.

2. Measure the voltage drop across C1 (V A to B) with the meter set on the 50 volt dc range and record the reading below.

   VC1 = _____

   This is the normal unloaded output voltage of a half-wave power supply.

3. Measure the voltage drop across C2 (V B to C) with the meter set on the 50 volt dc range and record the reading below.

   VC2 = _____

4. Measure the full (doubled) output voltage from A to C and record it below.

   V A to C = _____

   Calculate the sum of VC1 plus VC2 and record it below.

   VC1 + VC2 = _____

   Compare the above sum to the A to C measurement. Are they both the same voltages? _____

5. Measure the ac rms value of the T1 secondary from D to ground and record it below. (Use the panel meter on the 50 volt ac range).

   υ in rms = _____.

   Calculate the peak input voltage from:

   υ in pk = (Vrms) (1.414) = ( ) (1.414) = _____

   Is the dc output voltage measured in step 4 equal to twice the peak ac input voltage? _____

   Is the circuit acting as a voltage doubler? _____

7.2 Ripple Frequency Measurement

In this part of the experiment you will measure the ripple frequency of the output of the voltage doubler and compare it to the power line frequency.

6. In order to develop a ripple output voltage, it is necessary to connect a 10 K load resistor across the output, from A to C, as shown in Figure 2.

7. Observe and record the waveform seen at the voltage doubler output. Connect the oscilloscope, as shown in Figure 2,using the AC input to CH 1 and set the TIME/DIV control at 2 mS.

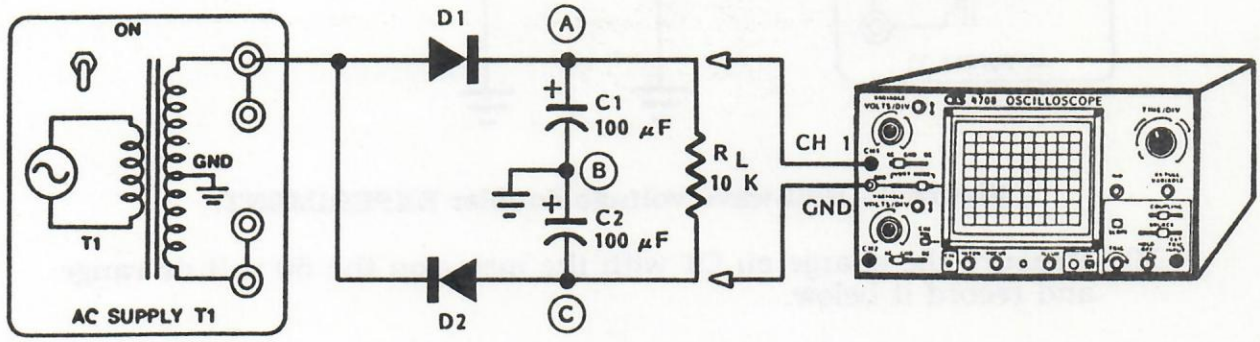


Figure 2 - Ripple observation EXPERIMENT.

8. Measure the period of one cycle of ripple voltage and record it below.

Period = (No of Div) (TIME/DIV) = ( ) (2 mS) = _____

Convert the period to frequency using:

f = 1 / Period = 1 / ( ) = _____

Your answer should be approximately 120 Hz plus or minus some small deviation due to error when reading the scope time base and also, scope calibration error. Note that the ripple frequency is equal to twice the power line frequency as in all full-wave rectifiers.

7.3 Half-Wave Voltage Doubler

In this part of the experiment you will wire a half-wave voltage doubler, measure the dc output voltage and compare it with the ac input voltage. You will then measure the ripple frequency in the dc output and compare it to the power line frequency.

9. Remove the full-wave doubler wiring and assemble the half-wave voltage doubler shown in Figure 3.

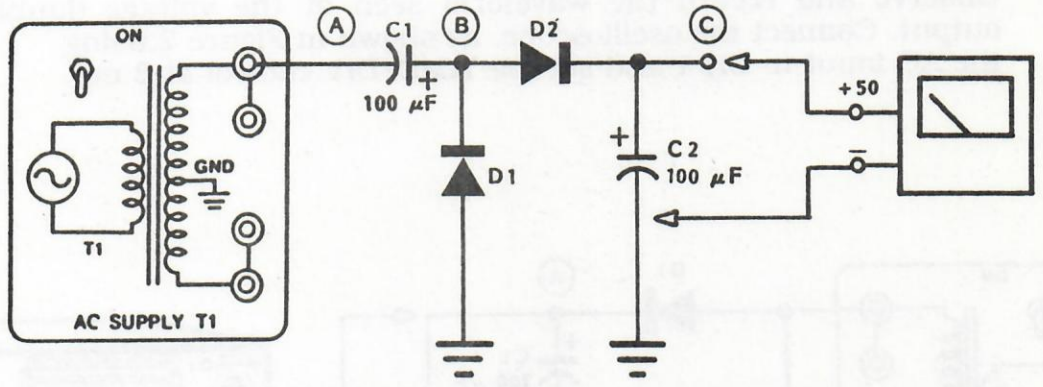


Figure 3 - Half-wave voltage doubler EXPERIMENT.

10. Measure the charge on C1 with the meter on the 50 volt dc range and record it below.

C1 Voltage = _____

11. Measure the doubler output voltage across C2 and record it below.

C2 Voltage = _____

Check the peak ac input voltage measured in step 5. Is the dc output voltage measured across C2 twice the peak ac input?

_____

12. Connect a 10 K load resistor across C2 of Figure 3 and observe the waveform on the oscilloscope.

13. Measure the period of one cycle of ripple voltage and record it below.

Period = _____mS

Convert the period to frequency using:

f = 1 / Period = 1 / ( ) = _____

The ripple frequency measurment will be close to 60 Hz.

Observe that the ripple frequency for the half-wave doubler is one half of the ripple frequency of the full-wave doubler and equal to the line frequency.

7.4 Voltage Tripler

In this part of the experiment we will expand the existing half-wave voltage doubler to a tripler by adding a third diode and capacitor pair.

14. Expand the circuit of the half-wave voltage doubler, presently wired, to the voltage tripler shown in Figure 4 by adding C3 and D3 shown in bold lines. Note that the output is taken from across C1 and C3.

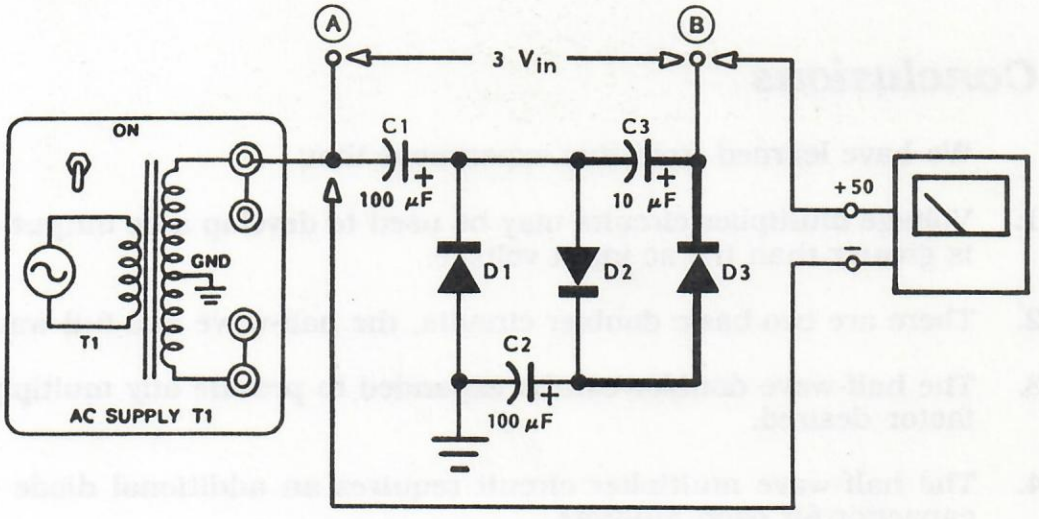


Figure 4 - Tripler circuit EXPERIMENT.

15. Record below the output voltage you expect to measure from the tripler in Figure 4, based on the vin pk from step 5.

Expected Tripler Output V A to B = _____

Measure the voltage from A to B in Figure 4 and record the reading below.

Measured Tripler Output V A to B = _____

How close are the theoretical and measured tripler output voltages?

_____

16. Record below the expected ripple frequency of the output of the voltage tripler.

Expected Tripler Ripple Frequency f = _____

17. Measure the ripple frequency of the output using the oscilloscope and record it below.

Measured Ripple Frequency f = _____

If the ripple frequency is not precisely equal to the line frequency it is due to errors in reading the oscilloscope time base or to calibration error.

Conclusions

We have learned from this experiment that:

1. Voltage multiplier circuits may be used to develop a dc output that is greater than the ac input voltage.
2. There are two basic doubler circuits, the half-wave and full-wave.
3. The half-wave doubler can be expanded to provide any multiplying factor desired.
4. The half-wave multiplier circuit requires an additional diode and capacitor for each multiple.
5. The half-wave multiplier output ripple frequency is equal to the power line frequency.
6. The full-wave doubler output ripple frequency is equal to twice the power line frequency.
7. The unloaded output of a voltage multiplier is equal to the peak ac input times the multiplier factor.

Assignment

Answer the following multiple choice questions.

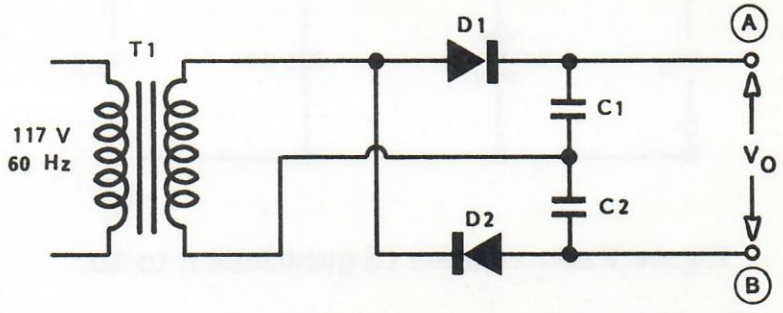


Figure 6 above refers to questions 1 to 5.

1. Given a T1 secondary voltage of 30 volts rms in the circuit of Figure 6, the output voltage, Vo, will be approximately: _____

   a) 30V.
   b) 42V.
   c) 60V.
   d) 84V.

2. The circuit of Figure 6 is a: _____

   a) voltage tripler.
   b) half-wave voltage doubler.
   c) full-wave voltage doubler.
   d) none of the above.

3. Given an output voltage of 100 volts dc for the circuit of Figure 6, the piv on the diodes would be: _____

   a) 200V on each.
   b) 100V on each.
   c) 100V on D1, 200V on D2.
   d) 200V on D1, 100V on D2.

4. The polarity of the output in the circuit of Figure 6 is: _____

   a) A+, B-
   b) B+, A-
   c) changing at a 60 Hz rate.
   d) changing at a 120 Hz rate.

5. The ripple output of Figure 6 has a measured period closest to: _____

   a) 8.33 nS
   b) 16.6 mS
   c) 8.3 mS
   d) none of the above

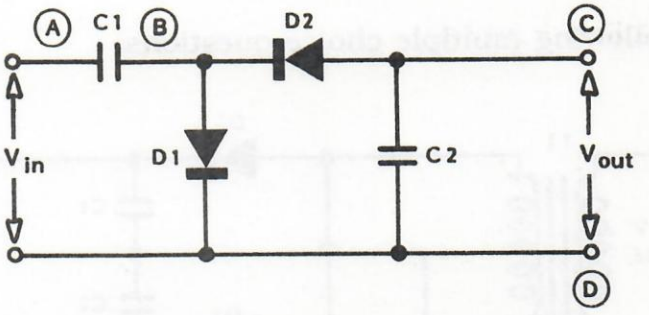


Figure 7 above refers to questions 6 to 10.

6. The circuit of Figure 7 is a: _____

   a) full-wave voltage doubler.
   b) half-wave tripler.
   c) full-wave tripler.
   d) half-wave voltage doubler.

7. The output polarity of the circuit of Figure 7 is: _____

   a) C+, D-
   b) D+, C-
   c) changing at a 60 Hz rate.
   d) changing at a 120 Hz rate.

8. Given an rms input voltage of 70 volts for the circuit of Figure 7, Vout will be approximately: _____

   a) 70V.
   b) 99V.
   c) 140V.
   d) 198V.

9. The piv seen by diode D2 in Figure 7, for 70 V rms input will be: _____

   a) twice the piv on D1.
   b) 99V.
   c) 140V.
   d) 198V.

10. The polarity of the charge on C1 in Figure 7 is: _____

    a) A+, B-
    b) B+, A-
    c) changing at a 60 Hz rate.
    d) changing at a 120 Hz rate.

11. The circuit of Figure 8 is a voltage: _____

    a) doubler.
    b) tripler.
    c) quintupler.
    d) regulator.

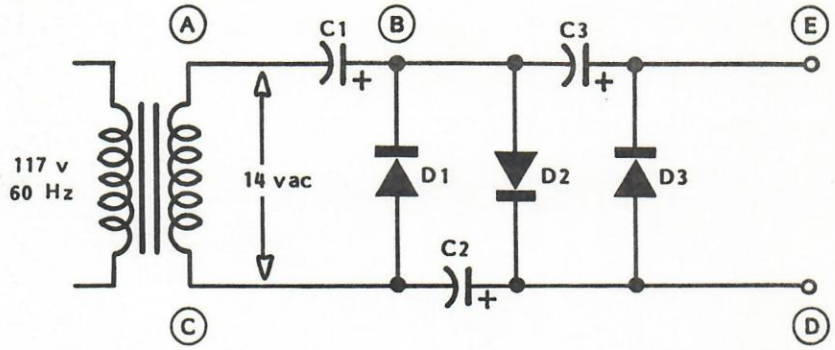


Figure 8 above refers to questions 11 to 14.

12. Given a T1 secondary voltage of 14 volts rms, the circuit of Figure 8 will produce a maximum output voltage, from A to E, of approximately: _____

    a) 14V. c) 39V.
    b) 28V. d) 59V.

13. The output voltage, measured from C to D in Figure 8, is approximately: _____

    a) 14V. c) 39V.
    b) 28V. d) 59V.

14. Draw the circuit of a half-wave voltage doubler with a 24 volts ac input voltage and calculate and show the peak dc output value and polarity.

15. Draw the circuit of a full-wave voltage doubler with a 117 volt power line input. Calculate and show the peak dc output voltage and the polarity. Add a surge resistor to limit the surge current to 25 amperes on the first half cycle of conduction.

Power Supply Troubleshooting 8

Objectives

When you have finished this experiment, you will be able to:

1. Test diodes using one of three procedures, analog ohmmeter, digital multimeter Diode Test setting and a voltmeter and voltage source.
2. Measure the dc and ac voltages in a power supply using an oscilloscope.
3. Locate typical power supply faults using a logical, orderly, test procedure.

Additional Equipment Required

Digital VOM

Reference

Information Sheet 5, Diode Testing and Troubleshooting

Procedure

8.1 Diode Testing Methods

In the first part of this experiment we will test the diodes on the trainer using several different test instruments.

Testing With An Analog Ohmmeter

1. Test diodes D1 to D4 , on the trainer panel, using an analog ohmmeter as shown in Figure 1.

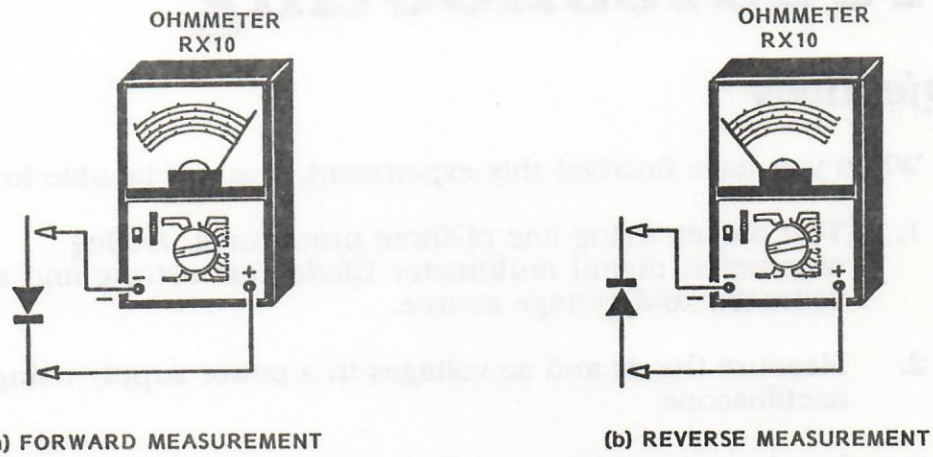


Figure 1 - Testing a diode's forward and reverse resistance; EXPERIMENT.

2. Record the forward and reverse resistances for D1 to D4.

DIODE	Rfwd	Rrev
D1		
D2		

DIODE	Rfwd	Rrev
D3		
D4		

Digital Multimeter Test

3. Test diodes D4 and D5 using the DIODE TEST function of the digital multimeter.

Record the forward and reverse readings in the spaces provided below.

DIODE	FORWARD	REVERSE *
D4 Si		
D5 Ge		

*The reverse or "open" state reading on the DVM is the same as that obtained with the test leads open or not connected into a circuit. The actual reading obtained will vary for different makes of digital voltmeters. Some will read "OL" (for overload) and others may read "1" (for overload or over range) and some will read a voltage value such as 1300 mV based on the internal circuitry of the DMM.

What is the "Open Lead" reading on your digital voltmeter?

DMM "Open" Reading = _____

How could you determine, from the voltage readings, which diode is germanium and which diode is silicon? _____

Testing With a Voltage Source and Meter

4. Wire the circuit shown in Figure 2.

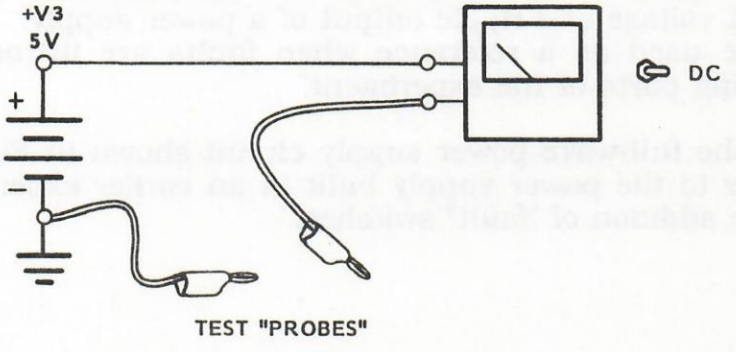


Figure 2 - Basic voltage test for diode junctions; EXPERIMENT.

5. Connect the two loose leads together to obtain a full-scale reading of 5 volts.

   Now, connect the leads across diodes D4 and D5, in turn, and observe and record the meter readings for forward and reverse states.

DIODE	FORWARD	REVERSE
D4		
D5		

Which diode is Si and how were you able to determine this? _____

_____

Why is there a reverse reading for diode D5? _____

_____

Why is the forward voltage reading higher than the reverse voltage reading? _____

_____

8.2 Normal Power Supply Operation

In this part of the experiment we will measure the normal dc output voltage and ripple output of a power supply. These values will be used as a reference when faults are introduced in the following parts of the experiment.

6. Wire the full-wave power supply circuit shown in Figure 3. It is similar to the power supply built in an earlier experiment except for the addition of "fault" switches.

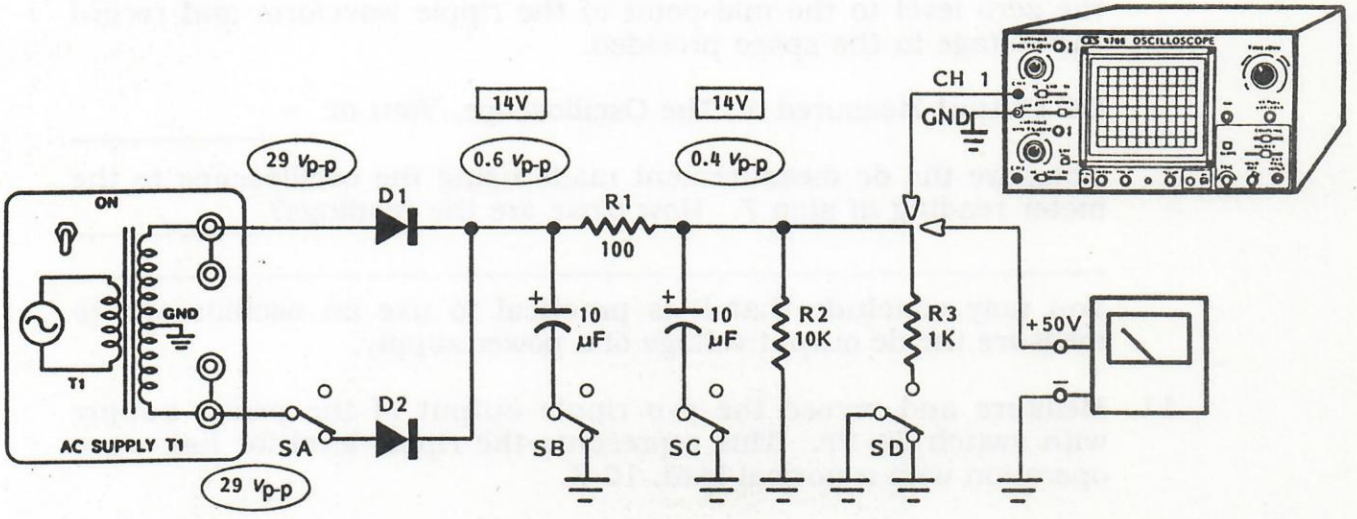


Figure 3 - Full-wave power supply circuit; EXPERIMENT.

The voltage values in the rectangles in Figure 3 are the "normal" expected dc readings. The voltage values in the elipses are the "normal" expected ac voltages, all with reference to ground. These voltages are supplied on circuit diagrams to aid in troubleshooting.

7. Set switches SA to SD in the DOWN position for normal power supply operation. Measure and record the dc output voltage as indicated on the trainer panel voltmeter.

   Normal DC Output, Vout dc = _____

8. Set the oscilloscope controls as follows:

CH1 V/DIV	2	TIME/DIV	2 mS
CH1 INP SW	GND	SOURCE	LINE
VERT MODE	CH1		

9. Adjust the position of the CH1 trace to the exact bottom of the screen (to represent zero volts).

   Move the CH1 Input Switch to DC.

10. Measure the dc output voltage, as indicated on the screen, from the zero level to the mid-point of the ripple waveform and record the voltage in the space provided.

    DC Output Measured on The Oscilloscope, Vout dc = _____

    Compare the dc measurement made using the oscilloscope to the meter reading in step 7. How close are the readings? _____

    _____

    You may conclude that it is practical to use an oscilloscope to measure the dc output voltage of a power supply.

11. Measure and record the p-p ripple output of the power supply with switch SA UP. This represents the ripple level for half-wave operation with a normal load, 10 K.

    To get an accurate measurement of the ripple voltage set the CH1 Input switch to AC, center the trace and increase the sensitivity to 0.2V/DIV.

    Record the p-p value of the ripple voltage.

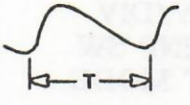
    Half-Wave Ripple Output, v ripple = _____ v p-p

12. Convert the p-p voltage to the approximate rms value as shown below.

    v rms = (v p-p / 2) 0.707 = [( ) / 2] 0.707 = _____

13. Measure the ripple frequency as shown below:

    f = 1 / T = 1/( ) = _____ Hz

    Note that the ripple frequency will be close to but not exactly equal to 120 Hz due to error in reading the scope screen and calibration error.

8.3 Ripple Problems

In this part of the experiment we will simulate ripple problems that are *not* accompanied by low dc output voltage. The faults introduced will raise the ripple level and leave the dc output unaffected.

14. Start with all the fault switches set in the DOWN position for normal operation. Move switch SC UP to remove C2 (open C2) from the filter circuit. Measure and record the new dc and ac output voltages.

    DC Meter Reading with C2 Open, Vout dc = _____

    Scope Ripple Reading with C2 Open, υ out ac = _____

    How are the output voltages affected? _____

    _____

    The increased ripple level may prevent the proper operation of the equipment powered by this supply.

15. Place switch SC in the DOWN position and set switch SB to the UP position.

    Measure and record the new dc and ac output voltages with C1 "open."

    Vout dc = _____ V (Meter Reading)

    Vout ac = _____ υ p-p (Scope Reading)

    How are the output voltages affected? _____

    _____

    The increased ripple may affect the operation of the equipment powered by this supply, but the slight drop in dc level will not affect the performance.

16. Set switch SB DOWN to restore the circuit to normal.

    Place switch SA to the UP position thus causing diode D2 to "open."

Measure and record the dc and ac output voltages with D2 "open."

Vout dc = _____ V (Meter Reading)

$v$out ac = _____ v p-p (Scope Reading)

17. Observe the ripple waveform on the oscilloscope and determine the ripple frequency from the period of one cycle.

$f$ripple = _____ Hz

Note that when one diode "opens" the dc output is barely affected but the ripple voltage is affected in two ways. First, the ripple frequency changes from 120 Hz to 60 Hz because the rectifier circuit is now half-wave. Second, because of the lower ripple frequency, the filter circuit is less effective and the ripple level is higher.

8.4 Low DC Output Problems

In this part of the experiment we will investigate the effects of an excessive load current on the dc and ac output of the power supply.

18. Start with all fault switches set in the DOWN position for normal operation. Place switch SD in the UP position to connect R3, 1K, across the output to act as a "partial short circuit."

Measure and record the new dc and ac output voltages with the "partial short circuit."

Vout dc = _____ V

$v$out ac = _____ v p-p

19. Explain why $v$out ac, the ripple voltage, increases in value. _____

_____

20. Measure the dc output directly at the rectifier diodes by moving the +50V lead of the meter to the junction of the D1, D2 cathodes. Record the voltage below.

V dc = _____ V

Explain why the two voltage readings, the dc output of the power supply and the dc output of the rectifiers, have dropped. _____

_____

We can conclude from the above that when there is excessive ripple in the output, it is possible, by examining the level of dc, to determine if the fault is due to open capacitors and diodes or a short in the filter circuit or load.

8.5 Troubleshooting

In this part of the experiment we will insert a fault in the full-wave power supply and locate the trouble using an oscilloscope and multimeter (either an analog or digital type).

22. Tape a small sheet of paper (6 inches) on to the trainer to cover switches SA to SD so their settings cannot be seen.

    Have your instructor or another student place only one of the switches, SA to SD, in the UP position and again cover the switches so the settings cannot be seen.

    Determine the fault using the measurement techniques developed in the previous steps of this procedure. Complete the Troubleshooting Table for each trouble inserted.

TROUBLESHOOTING TABLE 1

FAULT #	SYMPTOMS	TROUBLESHOOTING PROCEDURE	DEFECT
1			
2			
3			
4			

23. You will now insert troubles other than those offered by switches SA to SD. Do each of the following, one at a time, and complete Table 2.

    a. Remove a lead that connects to the T1 secondary to simulate an open section of the secondary winding.

    b. Add a shorting wire from one of the secondary terminals of T1 to ground to simulate a shorted transformer winding. (The transformer is protected and will not be harmed).

    c. Increase the value of R1 from 100 ohms to 100 K to simulate an open resistor.

    d. Substitute a 2 μF capacitor for one of the 10 μF capacitors to simulate a faulty capacitor that has lost capacitance.

TROUBLESHOOTING TABLE 2

FAULT #	SYMPTOMS	TROUBLESHOOTING PROCEDURE	DEFECT
a			
b			
c			
d			

Conclusions

We have learned from this experiment that:

1. Diodes may be tested using an analog ohmmeter, a digital multimeter that has a DIODE TEST position and a dc voltage source and a voltmeter.

2. A good diode reads a low resistance in one direction and infinity (or close to infinity) in the reverse direction.

3. Germanium diodes will show some leakage in the reverse direction when tested with an analog ohmmeter or a voltage source and voltmeter but this is normal.

4. A silicon diode exhibits a voltage drop of approximately 0.7 volts while a germanium diode has a drop of 0.3 volts.

5. An open diode in a full-wave rectifier will change the ripple frequency from 120 Hz to 60 Hz and increase the ripple level.

6. An open filter capacitor will increase the ripple level but may have only a small effect on the dc level. The ripple frequency will be unchanged, still 120 Hz.

7. A partially shorted filter capacitor will load down the power supply causing a reduced dc output and a higher ripple level (still at 120 Hz).

Assignment

Answer the following multiple choice questions.

1. A shorted diode, when tested with an analog ohmmeter, will read _____ in the forward direction and _____ in the reverse direction. _____

   a) low; low
   b) high; high
   c) low; high
   d) high; low

2. A normal diode when tested with a digital multimeter on the Diode Test position will read _____ in the forward direction and _____ in the reverse direction. _____

   a) 0.7; OL
   b) 0.3; 150 mV
   c) 0.7; 1
   d) any of the above.

3. A diode measures 50 ohms forward and 1 megohm reverse. The diode is: _____

   a) open
   b) shorted
   c) silicon
   d) germanium

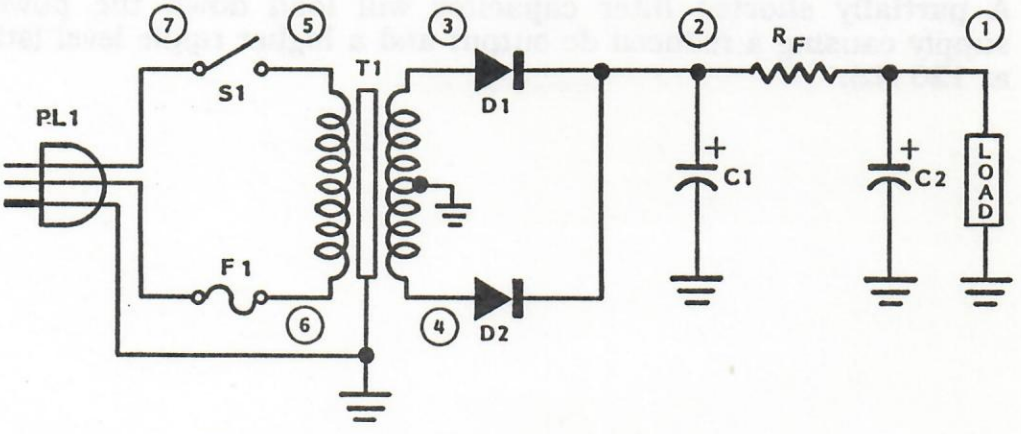


Figure 4 above refers to questions 4 to 10.

4. A 25 watt lamp may be wired in series with the transformer primary, in Figure 4, to: _____

   a) provide sufficient light by which to troubleshoot.
   b) limit the primary current to prevent F1 from blowing.
   c) protect the load from excessive voltage.
   d) all of the above.

5. If diode D1 open circuits, in Figure 4, the effect will be to: _____

   a) change the ripple from 60 Hz to 120 Hz.
   b) lower the ripple level.
   c) raise the ripple level.
   d) none of the above.

6. A scope check at point 1 in Figure 4 indicates no detectable ripple and a dc voltage of 1 volt instead of 12 volts. The possible cause is a (an): _____

   a) shorted filter resistor, RF.
   b) open filter resistor, RF.
   c) shorted diode, D2.
   d) open diode, D1.

7. A scope indicates a high 120 Hz ripple level at point 1 in Figure 4 but also shows a normal dc level. A possible cause is an: _____

   a) open filter capacitor (C1 or C2).
   b) open section on the T1 secondary.
   c) open diode (D1 or D2).
   d) none of the above.

8. A high 120 Hz ripple and a lower than normal dc output voltage at point 1 in Figure 4, may be the result of a: _____

   a) partially shorted filter capacitor, C1.
   b) partially shorted filter capacitor, C2.
   c) partial short somewhere in the load.
   d) all of the above.

9. In the circuit of Figure 4, no ac voltage is present from points 3 and 4 to ground. The possible cause for this is a (an): _____

   a) open switch, S1
   b) blown fuse, F1
   c) open T1 secondary center tap.
   d) all of the above.

10. In the circuit of Figure 4, the fuse (F1) blows out each time it is replaced and S1 is turned on. A possible fault is a (an): _____

    a) open capacitor, C1.
    b) open capacitor, C2.
    c) shorted turn or turns on the T1 secondary.
    d) none of the above.

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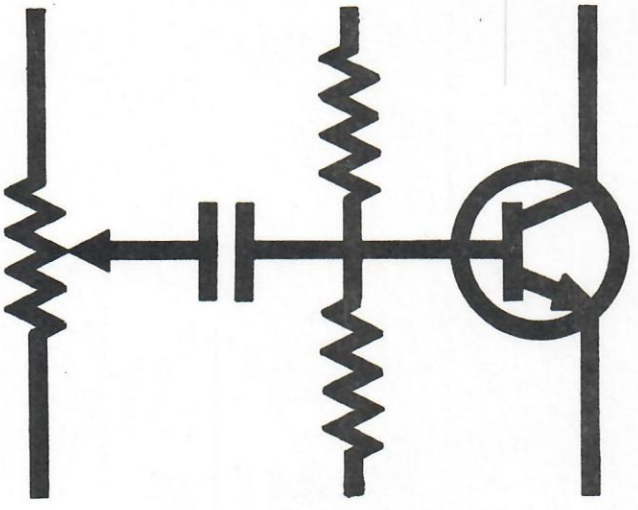

J1

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PART J1

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ISBN 0-86711-139-9
Printed in United States of America

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PART J1-TRANSISTORS AND CIRCUITS

Table of Contents

		Safety Lesson
Info. Sheet	1	Bipolar Transistors
Lesson No.	1	Transistor Testing Methods
Experiment	1	Transistor Testing
Lesson No.	2	Transistor Voltages
Experiment	2	Transistor Action
Info. Sheet	2	Transistor Characteristic Curves
Info. Sheet	3	Transistor Models
Lesson No.	3	Common Emitter (CE) Transistor Amplifier Gain
Experiment	3	Common Emitter (CE) Amplifier Operation
Lesson No.	4	Emitter Degeneration Effects
Experiment	4	Emitter Degeneration
Lesson No.	5	Biasing Circuits
Experiment	5	Transistor Bias Stability
Lesson No.	6	Voltage-Divider Bias Design
Experiment	6	Voltage-Divider Biased Amplifier Operation
Lesson No.	7	Input-Output Impedances
Experiment	7	I-O Impedance Measurements
Experiment	8	Characteristic Curves
Lesson No.	9	Common Collector (CC) Amplifier Circuits
Experiment	9	Common Collector (CC) Amplifier Operation
Lesson No.	10	Common Base (CB) Amplifier Circuits
Experiment	10	Common Base (CB) Amplifier Operation
Info. Sheet	4	Transistor Specification Sheets

Name _____

Class _____

School _____

STUDENT PROGRESS RECORD & GUIDE FOR PART J1

EXP./INFO.	TITLE	ASSIGNMENT		GRADE
		DATE DUE	DATE SUBMITTED	
Info. Sheet 1	Bipolar Transistors			
Lesson No. 1	Transistor Testing Methods			
Experiment 1	Transistor Testing			
Lesson No. 2	Transistor Voltages			
Experiment 2	Transistor Action			
Info. Sheet 2	Transistor Characteristic Curves			
Info. Sheet 3	Transistor Models			
Lesson No. 3	CE Transistor Amplifier Gain			
Experiment 3	CE Amplifier Operation			
Lesson No. 4	Emitter Degeneration Effects			
Experiment 4	Emitter Degeneration			
Lesson No. 5	Biasing Circuits			
Experiment 5	Transistor Bias Stability			
Lesson No. 6	Voltage-Divider Bias Design			
Experiment 6	Biased Amplifier Operation			
Lesson No. 7	Input-Output Impedances			
Experiment 7	I-O Impedance Measurements			
Experiment 8	Characteristic Curves			
Lesson No. 9	CC Amplifier Circuits			
Experiment 9	CC Amplifier Operation			
Lesson No. 10	CB Amplifier Circuits			
Experiment 10	CB Amplifier Operation			
Info. Sheet 4	Transistor Specification Sheets			

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TRANSISTORS AND CIRCUITS
PART J1

Safety Lesson

OBJECTIVES

When you finish this Information Sheet you will be able to:

1. List three general danger areas that may be encountered in Electrical and Electronics work.
2. List four possible effects of an electrical shock to the body.
3. List two ways to remove a shock victim from the power source.
4. Define Class A, Class B and Class C fires.
5. Specify the types of fire extingushers that can be used for electrical fires.
6. Identify True and False statements about hand tools.

DESCRIPTION

When working with electrical and electronic equipment there are several dangers that may be encountered. These are:

A. Electrical Shock
B. Electrical Fire
C. Hand Tool Injuries

In order to avoid these hazards, you will have to observe proper precautions and avoid irresponsible behavior. You must also learn to recognize dangerous conditions and report them to your instructor.

A. Electrical Shock results from contact with a source of electricity strong enough to stimulate the flexor muscles. Depending on the strength of the shock and its path through your body, it can cause you to:

1. Feel a tingling sensation
2. Jump back and break free
3. Freeze on the circuit, unable to let go
4. Stop breathing
5. Go into ventricular fibrillation, a condition where the heart beats wildly, out of rhythm, and so pumps little or no blood.

Conditions 3, 4 and 5 can lead to death unless treated immediately. Condition 3 requires that the victim be removed from the source of power as soon as possible and in a manner that does not endanger the rescuer. If you cannot turn off the power and remove the victim then use a jacket, shop apron, a long piece of wood, or any type of nonconductor to loop over the body and pull the victim loose. If the victim has stopped breathing begin artificial respiration immediately while someone goes for help. Artifical respiration is also required for conditions 4 and 5 above. See detailed instructions.

The Ed-Lab equipment has been designed so that it presents no shock hazard. Despite this, you should be careful, particularly when using other pieces of test equipment with the Ed-Lab 651.

Some basic rules for electrical safety are:

1. Do not perform electrical/electronic work in damp areas.
2. Do not assume power is off; check it.
3. Do not defeat safety switches (interlocks).
4. Do not remove the ground wire from equipment.
5. Do not use power plug adaptors (from 3 wire to 2 wire) to remove ground leads.

B. Electrical Fires that result from short circuits and overheating in electrical/electronic devices are listed as Class C fires. Only two types of fire extinguishers are to be used for electrical/electronic fires; Carbon Dioxide (CO_2) and Dry Chemical. See Figure 1.

C. Hand Tool Injuries - Electronics technicians use a wide variety of hand tools and some power tools to construct, repair and maintain equipment. If used improperly or in a careless manner the tools can cause injuries. The safe use of hand tools can be summarized in three statements. Use a tool properly. Use a tool only for the purpose it was intended. Keep all tools in good working condition.

Several important cautions for hand tools are:

Be careful when using soldering irons or soldering guns; they can cause painful burns and fires.

When using a wrench, pull on it rather than push.

Be sure hammer heads are tightly fastened to their handles before using them.

When using power tools, keep the line cord clear of the work.

Check the line cords of all power tools. Do not use if they have cracks or exposed wires.

When drilling, fasten the work so that it will not spin.

Be sure that all power tools have a 3 wire plug; do not use 3 wire to 2 wire adaptors to defeat the ground.

Wear safety goggles whenever the work produces flying chips.

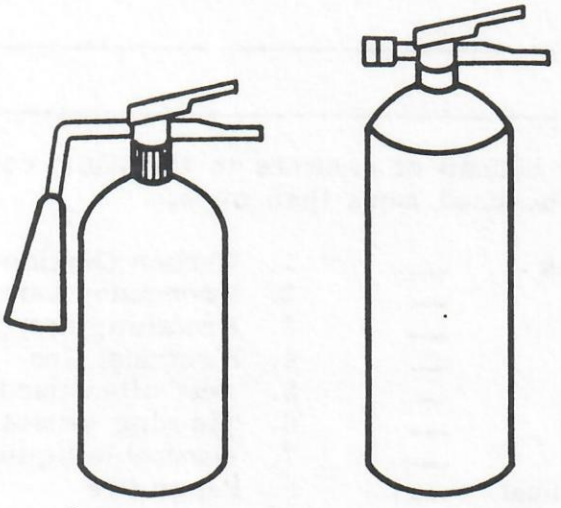


Figure 1 - Two types of fire extinguishers suitable for use in Class C fires (electrical/electronic). They may also be used for Class A fires (paper and rubbish) and Class B fires (flammable liquids such as oil, gasoline, paint, etc.). Because they can be used for Class A, B and C fires, they are very popular types of extinguishers.

ASSIGNMENT

1. List two ways to remove a shock victim from contact with an electrical circuit without endangering yourself.

   A. _____

   B. _____

2. List three dangers that may be encountered in an electronics laboratory.

   A. _____

   B. _____

   C. _____

3. Match the left column of answers to the right column. Answers may be used more than once.

A. Mild Shock	___	1. Carbon Dioxide
B. Class A	___	2. Emergency care
C. Class B	___	3. Breathing stopped
D. Class C	___	4. Electrical fire
E. Death	___	5. Most often used
F. CO_2	___	6. Tingling sensation
G. First aid	___	7. Flammable liquids
H. Dry Chemical	___	8. Paper fire

4. Indicate which of the following statements are True or False.

   A. It is safe to cut the ground pin off a 3 wire power plug when necessary. _____

   B. Clamp down any work that is being drilled. _____

   C. Soldering irons are one of the safest hand tools used by a technician. _____

   D. Safety goggles need not be worn if you already wear glasses for improved vision. _____

   E. Check all power cords before use. _____

FIRST AID FOR ELECTRICAL SHOCK

IF YOU OBSERVE AN ACCIDENT INVOLVING ELECTRICAL SHOCK,

DON'T JUST STAND THERE - DO SOMETHING !

RESCUE OF SHOCK VICTIM

The victim of electrical shock is dependent upon you to give him prompt first aid. Observe these precautions:

1. Shut off the high voltage.

2. If the high voltage cannot be turned off without delay, free the victim from the live conductor. REMEMBER:

   a. Protect yourself with dry insulating material.

   b. Use a dry board, your belt, dry clothing, or other non-conducting material to free the victim. When possible PUSH - DO NOT PULL the victim free of the high voltage source.

   c. DO NOT touch the victim with your bare hands until the high voltage circuit is broken.

FIRST AID

The two most likely results of electrical shock are: bodily injury from falling, and cessation of breathing. While doctors and rescue equipment are being sent for, DO THESE THINGS:

Control any bleeding by use of a pressure or a tourniquet.

Begin IMMEDIATELY to use artificial respiration if the victim is not breathing or is breathing poorly.

ARTIFICIAL RESPIRATION

1. Turn victim on back.

2. Clean the mouth, nose, and throat. (If they appear clean, start artificial respiration immediately. If foreign matter is present, wipe it away quickly with a cloth or your fingers).

3. Place the victim's head in the "sword-swallowing" position. (Place the head as far back as possible so that the front of the neck is stretched).

4. Hold the lower jaw up. (Insert your thumb between the victim's teeth at the midline - pull the lower jaw forcefully outward so that the lower teeth are further forward that the upper teeth. Hold the jaw in this position as long as the victim is unconscious).

5. Close the victim's nose. (Compress the nose between your thumb and forefinger).

6. Blow air into the victim's lungs. (Take a deep breath and cover the victim's open mouth with your open mouth, making the contact air-tight. Blow until the chest rises. If the chest does not rise when you blow, improve the position of the victim's air passageway, and blow more forcefully. Blow forcefully into adults, and gently into children.

7. Let air out of the victim's lungs. (After the chest rises, quickly separate lip contact with the victim allowing him to exhale).

8. Repeat steps 6 and 7 at the rate of 12 to 20 times per minute. Continue rhythmically without interruption until the victim starts breathing or is pronounced dead. (A smooth rhythm is desirable, but split-second timing is not essential).

DON'T JUST STAND THERE - DO SOMETHING !

Bipolar Transistors

INFO SHEET 1

OBJECTIVES

When you finish this information sheet you will be able to:

1. Define what is meant by a passive and an active device.
2. Define what is meant by amplification.
3. Describe the two basic types of bipolar transistors.
4. Explain the behavior of a conductor, semiconductor and insulator in a series circuit.
5. Describe the formation of a PN junction and the barrier potential.
6. Draw the schematic symbols for the PNP and NPN transistors.
7. Draw cross-sections showing the construction of typical alloy and diffusion transistors and integrated circuits.
8. Explain how the current flow from the emitter separates between the base circuit and collector circuit.
9. Describe how a small input base current can control a large output collector current.
10. Define what is meant by current gain, beta and H_{fe}.
11. Calculate the current gain of a transistor amplifier.

DISCUSSION

Up until now, the components we have worked with have been resistors, capacitors, inductors, transformers and lamps in dc and ac circuits. The semiconductor diode was also studied. Each of these components, when placed in a circuit, resulted in a power loss. Devices that introduce a power loss and do not amplify or increase power, are considered to be PASSIVE DEVICES.

The semiconductor TRANSISTOR is the device to be studied now and is used in a circuit to provide AMPLIFICATION, that is, to provide a voltage or power output that is greater than its input. The transistor is thus called an ACTIVE DEVICE and accomplishes amplification by using a low input power to control the high output power which is obtained from a separate power source or power supply.

TRANSISTOR TYPES

One group of transistors is made with a combination of both P-type and N-type materials, as in the diode covered previously, but in the combinations shown in Figure 1. Also shown are the circuit symbols for each type of transistor. Note that the only difference in symbols is that arrow points inward for the PNP and outward for the NPN. If you have not reviewed the semiconductor diode lessons before this information sheet, then helpful material describing the atomic structure of semiconductors is given in Unit H, Information Sheet 1, Solid State PN Junctions.

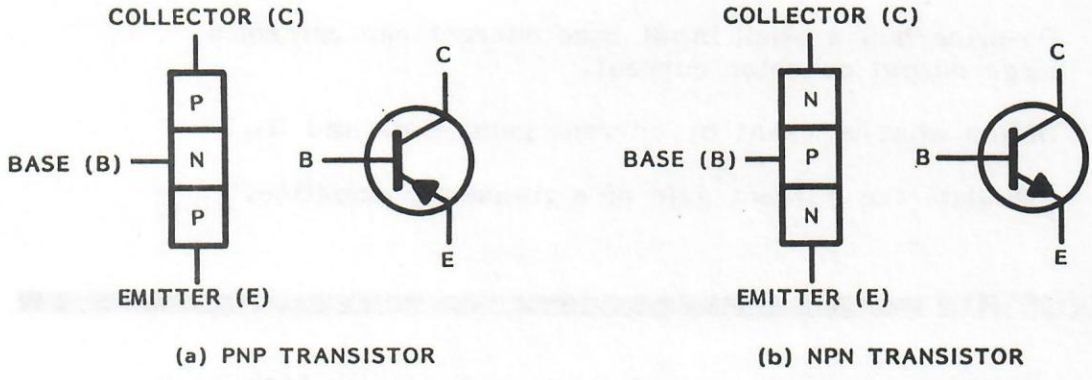


Figure 1 - PNP and NPN bipolar transistor construction and symbols.

The transistors shown in Figure 1 are called BIPOLAR JUNCTION TRANSISTOR types (BJT) because, when current flows from emitter to collector, or collector to emitter, the current must flow through two (bi) types of material, P and N. The three wires to the transistor are called the EMITTER (emits electrons), BASE, and COLLECTOR (collects the electrons).

Another type of transistor is the FIELD EFFECT TRANSISTOR or FET. This is a UNIPOLAR device because current flow in the FET is through one (uni) type of material only, N or P, from source (S) to drain (D), as shown in Figure 2.

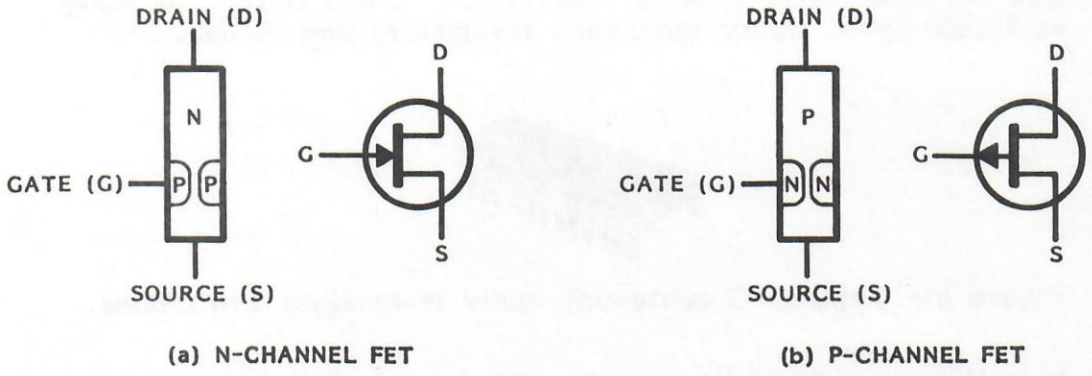


Figure 2 - N and P type field effect transistors (FET).

The symbol for the N-CHANNEL FET in Figure 2(a) shows the arrow pointed inward while for the P-CHANNEL FET, the arrow direction is reversed as in Figure 2(b). The FET will be studied in detail in later modules. The bipolar transistor will be studied in the first sequence of lessons and experiments.

VACUUM TUBES

Still a third type of active device is shown in Figure 3, the VACUUM TUBE. The vacuum tube or simply the "tube," is an active device that has been in use since the year 1907 until the late 1950's when it was replaced by the transistor. Some vacuum tubes are still used today in those special applications for which transistors are not suitable. Vacuum tubes operate in a manner similar to the N-channel FET. The vacuum tube will also be covered in later experiments.

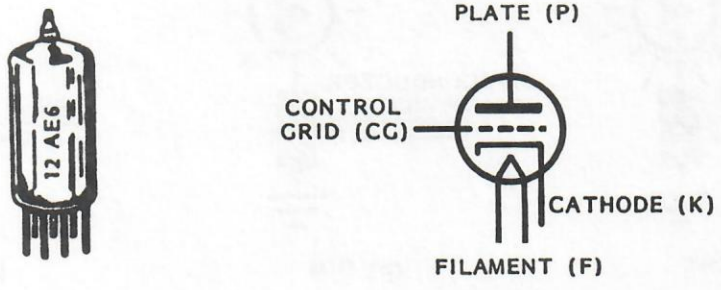


Figure 3 - The vacuum tube appearance and its circuit symbol.

INTEGRATED CIRCUITS

The modern INTEGRATED CIRCUIT, abbreviated IC, is illustrated in Figure 4, approximately in its actual size. Typically this IC, also referred to as a MICROCHIP, can contain as many as 30,000 (yes, thirty thousand) transistors and diodes.

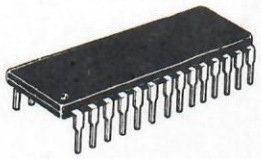


Figure 4 - Typical IC containing many transistors and diodes.

It is this microchip with its many thousands of transistors and diodes that is the basis of today's personal computers and high technology era.

SEMICONDUCTORS

In our earlier study of dc electricity, the differences between CONDUCTORS and INSULATORS were discussed relative to their ability to conduct electricity (the flow of electrons). The conductor has very little opposition to current flow, close to zero ohms. The insulator has enormous opposition to the flow of current, measured in thousands of megohms of resistance. N-type and P-type semiconductor materials have characteristics that fall between conductors and insulators. When placed in a circuit, the semiconductor materials act as poor conductors (or poor insulators). Placing a conductor, a semiconductor device and an insulator in a series circuit, will produce the results illustrated in Figure 5.

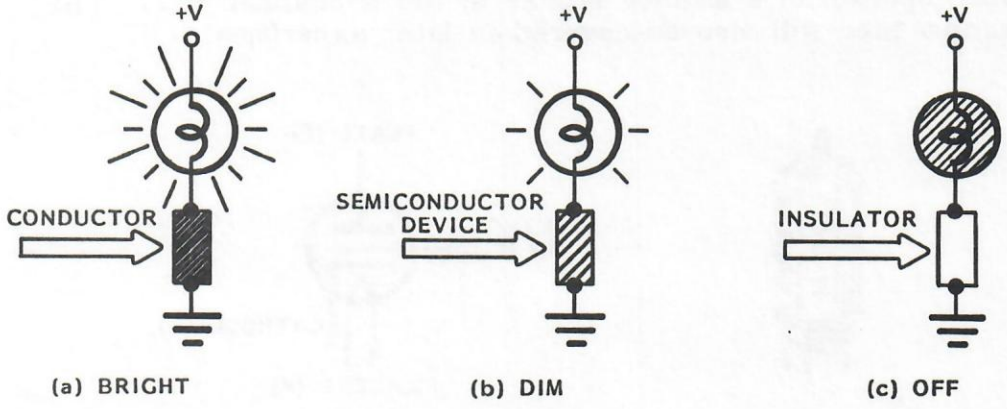


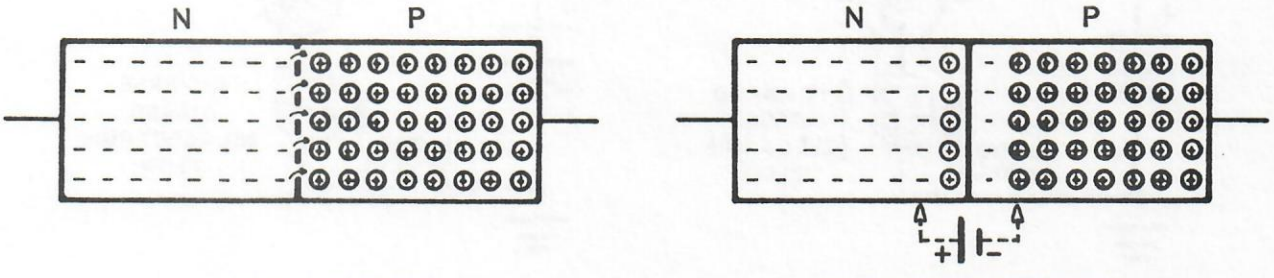
Figure 5 - Effects of conductor, semiconductor and insulator in a circuit.

Semiconductor materials, discussed previously with respect to diodes, indicated that the most commonly used materials are silicon (Si) and germanium (Ge). We will provide a review of the diode PN junction operation because it is essential for an understanding of transistor operation.

Pure silicon (or germanium) is doped with IMPURITIES to form two different types of semiconductors, P-type when Boron (B) is added and N-type when Arsenic (As) is added. The P-type material has too few electrons to complete the covalent bonding structure thus leaving "Holes" that can be filled later by additional electrons. It thus has "floating" POSITIVE charges and hence the term P-type. The N-type material is doped with an impurity that has too many electrons and so, after the covalent bonding is formed, extra electrons float through the structure unattached. It thus has "floating" NEGATIVE charges and hence the term N-type. Both P and N-type materials, however, are neutral with equal positive and negative charges because they each contain an equal number of protons and electrons even though some of the electrons in the N-type material are not in the bonding structure and are free to move.

BARRIER POTENTIAL

When the P and N-type materials are combined to form a PN JUNCTION we have a semiconductor DIODE, a two terminal passive device. The diode will conduct current in one direction only. The moment the junction is formed, the free electrons near the junction in the N-type material begin to move across the junction to fill the holes in the P-type material as shown in Figure 6(a).



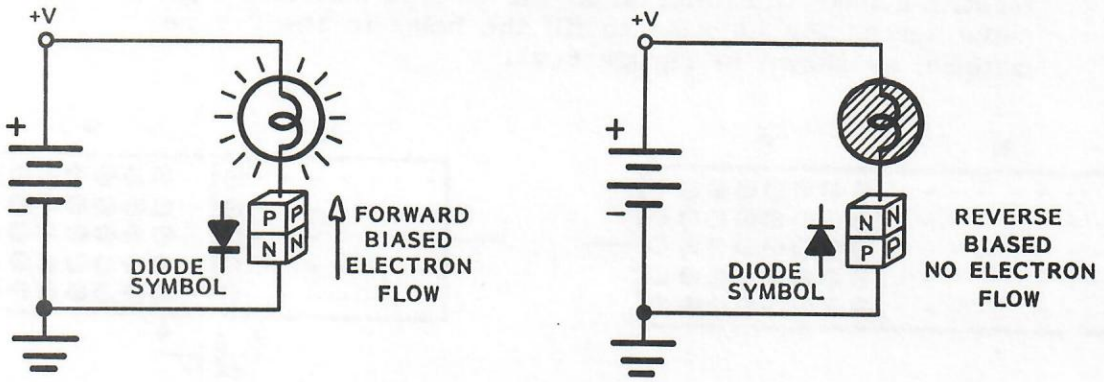
(a) ELECTRON MOVEMENT (b) BARRIER POTENTIAL

Figure 6 - Electron movement across junction and the resulting barrier potential.

As the electron movement across the junction continues to fill the holes, the P-type material begins to build up a negative charge. Equilibrium in potential forces attracting electrons is reached when the negative charge on the P-type material is so great that no more electrons can cross the junction. Because there are now more electrons in the P-type material and fewer electrons in the N-type material, a difference of potential, a voltage, called the BARRIER POTENTIAL, has been created across the junction as shown in Figure 6(b). It is this barrier potential that prevents the further migration of electrons across the diode junction. When silicon is used, the barrier potential becomes 0.7 volts and for germanium it becomes 0.3 volts. When we want the diode to conduct, the externally applied voltage must be greater than the barrier potential and of the correct polarity. When the diode does conduct, the voltage drop across the diode is not zero as it would be for a closed switch. The voltage drop across a conducting silicon diode is typically 0.7 volts and across a conducting germanium diode it is typically 0.3 volts.

DIODE CONDUCTION

The P-N junction is a diode, a two terminal passive device, which conducts an electron current flow in one direction, from N to P, as shown in Figure 7(a). When connected in this manner, the +V potential, when greater than the barrier potential, overcomes the barrier potential to allow the continuous flow of electron current from the N to P regions.



(a) CONDUCTING DIODE

(b) NON-CONDUCTING DIODE

Figure 7 - Forward and reverse biased diodes.

When the diode is reversed, as in Figure 7(b), no current flows across the PN junction because the barrier potential is

reinforced by +V and there is no conduction from the P to N regions.

TRANSISTOR CONSTRUCTION

The TRANSISTOR is a three terminal active device made up of an arrangement of three semiconductor elements, PNP or NPN, as shown in Figure 8(a).

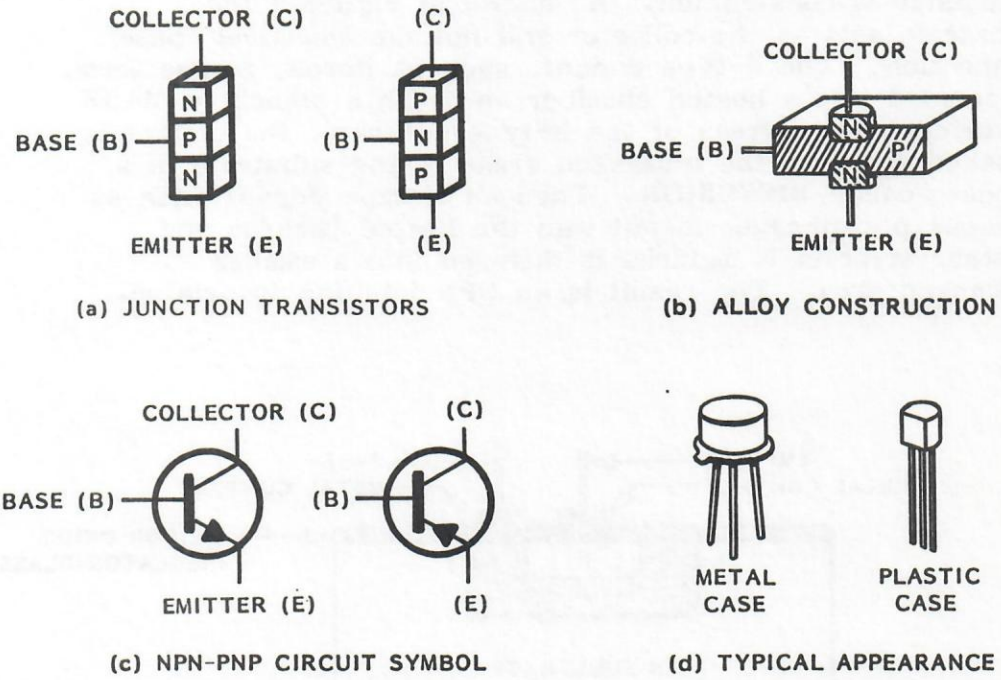


Figure 8 - Transistor construction, symbols and appearance.

The actual construction of a simple transistor using the ALLOY method is shown in Figure 8(b). There are many newer methods of constructing a transistor other than the alloy process. New techniques are being developed continually and descriptions of these methods can be found in many standard texts. Basically, all bipolar transistors consist of an NPN or PNP sequence of semiconductor materials and can be considered as shown in Figure 8. In Figure 8(b), we see that N-type materials have been deposited on a P-type base material and, using heat, diffused into the base structure, hence the name BASE for the middle section of the transitor.

The "alloy method" has been used to produce billions of germanium transistors and diodes. But problems arise when using the alloy method with silicon because of its high melting point and because it is difficult to control the very thin base required for high gain and high operating speed.

DIFFUSED JUNCTION PROCESS

A widely used process for manufacturing transistors and integrated circuits (ICs) using silicon, is called the DIFFUSED JUNCTION PROCESS. This process also begins with a doped semiconductor base, called a SUBSTRATE, such as shown in Figure 9. In this case the term "base" is purely structural and the substrate is the base upon which the transistor is constructed. As shown in Figure 9 the substrate acts as the collector and not the electrical "base" connection. The P-type dopant, such as Boron, in gas form, is pumped into a heated chamber and with a stencil or MASK covering certain areas of the N-type subtrate, the dopant is "soaked up" into the unmasked areas of the substrate in a process called DIFFUSION. Then an N-type dopant such as gaseous phosphorus, is put into the heated furnace and another layer of N material is diffused into a smaller unmasked area. The result is an NPN junction transistor.

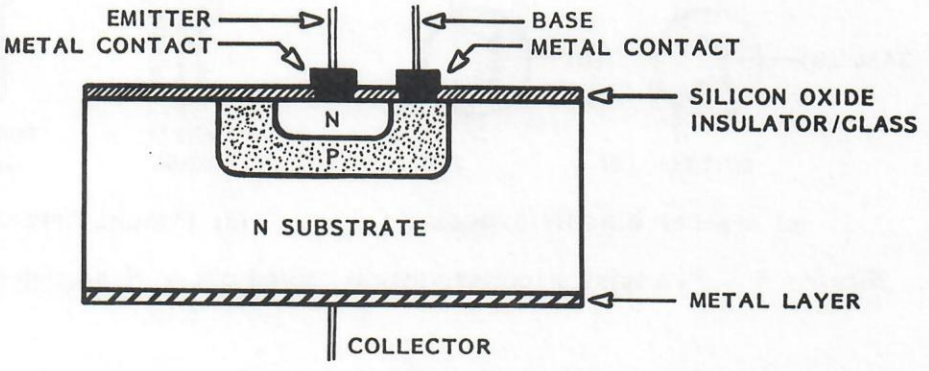
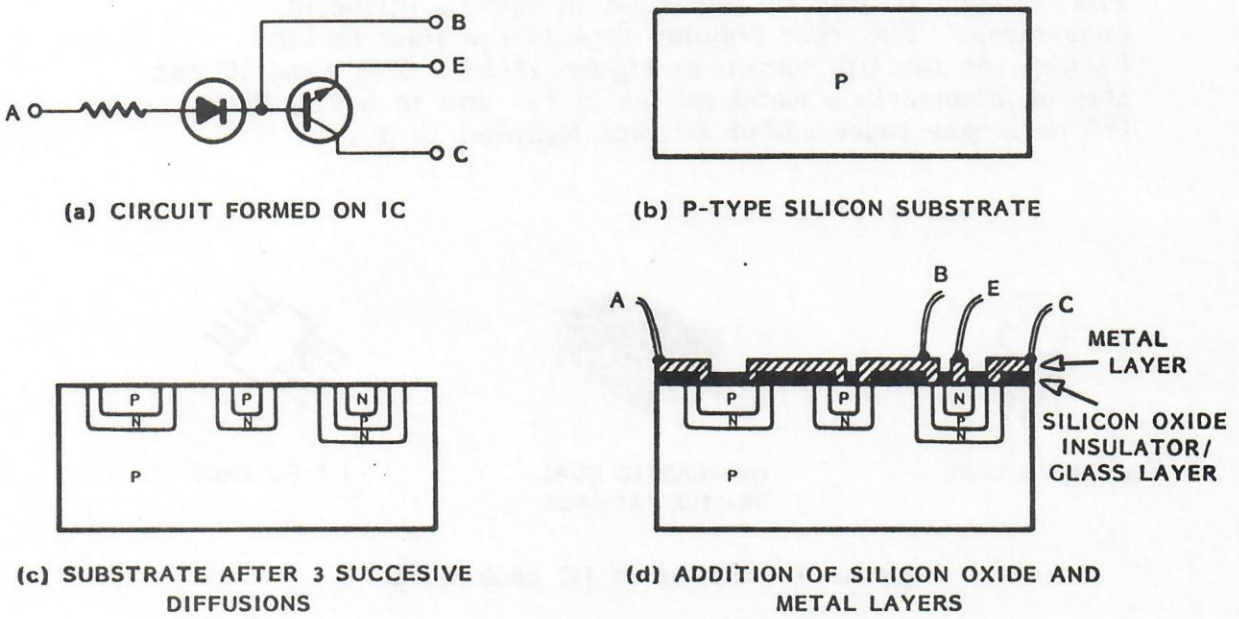


Figure 9 - An NPN transistor formed through the diffusion process.

A thin layer of metal is plated on the bottom of the substrate which is the collector as shown in Figure 9. A layer of insulation is formed on the top side of the substrate. This is done by combining oxygen or an OXIDE with the silicon surface to create SILICON OXIDE which is glass and an excellent insulator. The mask used when forming the silicon oxide leaves two open areas to allow metal contacts to be formed on the base and emitter areas. The entire assembly is then placed in a plastic or metal housing, called a CASE, with three connecting wires.

INTEGRATED CIRCUITS

Integrated circuits are made using a diffusion method also referred to as PLANAR DIFFUSION. The reason for this is that the semiconductor diffusions are all made on the same surface or "plane." An integrated circuit is a combination of many transistors, diodes and resistors on a single substrate. A simplified illustration of how a complete circuit is formed on a single semiconductor substrate "slice" is illustrated in Figure 10.



(a) CIRCUIT FORMED ON IC

(b) P-TYPE SILICON SUBSTRATE

(c) SUBSTRATE AFTER 3 SUCCESIVE DIFFUSIONS

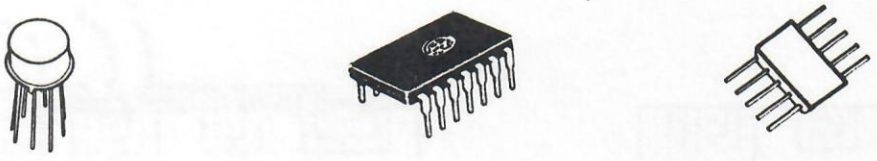
(d) ADDITION OF SILICON OXIDE AND METAL LAYERS

Figure 10 - Simple illustration of the diffusion process used for complex integrated circuits.

The simple circuit to be formed on the substrate is shown in Figure 10(a) and the P-type substrate on which it is to be formed in (b). The N and P dopants are then diffused into the substrate in three diffusion operations to form the areas shown in (c). The insulating layer of silicon oxide is then formed, masked properly to allow connection to the necessary areas. This is followed by a metallic layer that interconnects the areas to form the circuit and act as contact points for connecting leads. The lead marked A connects to one end of the P section that acts as a

resistance. The resistance value is controlled by the length and cross sectional area of the P section as well as the dopant level. The right end of the resistor section is connected to the anode of the diode formed by the center PN junction. The N section of the diode, the cathode, is connected by a metallic layer to the base of the NPN transistor that was formed on the right end of the substrate. Leads are then connected to the metallic areas formed over the emitter and collector areas. Each of the components formed is insulated from the others by the formation of a barrier potential between each N section and the P-type substrate; this blocks conduction.

The finished IC may be packaged in several different enclosures. The most popular type is the Dual In-Line Package or the DIP shown in Figure 11(b). The same IC can also be housed in a metal can as in (a) and in a Flat Pack, (c) or larger cases called Surface Mounted Units.



(a) METAL CASE

(b) PLASTIC DUAL IN-LINE PACKAGE

(c) FLAT PACK

Figure 11 - Types of IC packaging.

Thousands of resistors and transistors can be manufactured on a silicon substrate. The nomenclature relating to how complex an IC is, may be defined by the number of digital circuits contained and is listed as:

Small Scale Integration	SSI	Up to 9 circuits
Medium Scale Integration	MSI	10 to 100 circuits
Large Scale Integration	LSI	100 to 1000 circuits
Very Large Scale Integration	VLSI	Over 1,000 circuits

Very Large Scale integrated circuits may contain up to as many as 50,000 circuits requiring as many as 500,000 components (transistors, diodes, resistors, or even capacitors which are reverse biased diodes) all deposited on a single, small, silicon substrate called a CHIP or MICROCHIP often less than 1/8 inch square.

CONSTRUCTION METHODS

The method of preparing the substrate, of masking, of depositing P and N dopants and controlling their depth requires very precise control of temperature, density of the dopants and timing. As a brief outline, the process consists of the following steps:

1. Purified melted silicon (taken from ordinary sand) is placed in a dish or "crucible." The silicon crystals in the dish are "poly" crystalline which means that the crystal structure is not in order but "jumbled up." A small "seed" crystal is lowered into the melted silicon and it is rotated and drawn out slowly. As the silicon seed crystal is drawn out, the molten silicon adheres to the seed crystal and cools to form a "grown" crystal with a "mono" crystalline or "even-symmetrical" structure and a diameter of up to two inches as shown in Figure 12. This grown crystal is often called an INGOT.

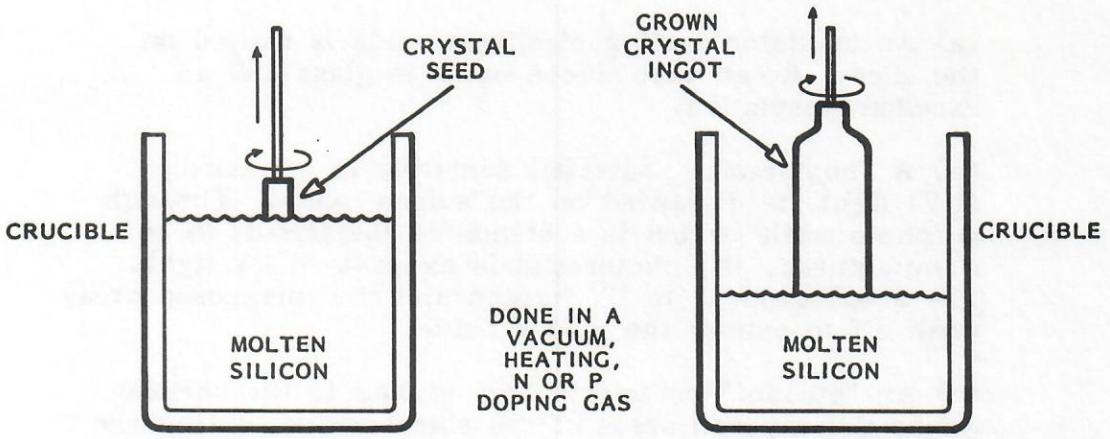
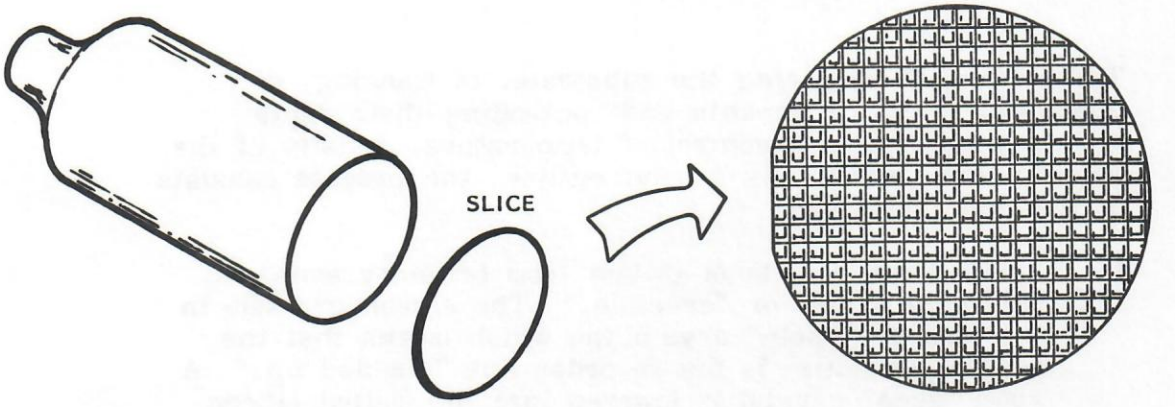


Figure 12 - Pulling a silicon crystal.

2. The grown crystal is "sliced" into wafers or round discs called silicon slices as shown in Figure 13. These silicon slices are large enough to eventually contain hundreds of ICs per slice. The ICs on the wafer are later cut apart and each chip is mounted in its own package.



(a) GROWN SILICON CRYSTAL INGOT

(b) SILICON SLICE WITH HUNDREDS OF INTEGRATED CIRCUITS READY TO BE CUT UP

Figure 13 - Grown crystal ingot, silicon slice and ICs on a slice.

3. The process of producing stencils and masks is as follows:

(a) An insulator coating of silicon oxide is formed on the slice. Recall that silicon oxide is glass and an excellent insulation.

(b) A "photoresist" material, sensitive to ultraviolet (UV) light, is deposited on the silicon oxide. Through a "photo mask" which is a stencil of the circuit to be manufactured, the photoresist is exposed to UV light. The areas exposed to UV harden and the unexposed areas wash off to expose the silicon oxide.

(c) An "etchant" or acid is now applied to the surface where the exposed areas of the silicon oxide coating are etched away thus exposing the silicon substrate. The areas covered by the photoresist are unaffected. After the etching is completed, the photoresist is washed off.

(d) The N and P type gases are now applied in the required order, at specific densities, temperatures and time, to diffuse into the substrate.

(e) A layer of metal is placed over the silicon dioxide in a process called METALLIZATION. The metallized layer is coated with a photoresist. A mask with the wiring pattern is placed over the photoresist and exposed to UV light. An etchant or acid now removes the unwanted metal leaving the desired wiring pattern that was on the photo mask.

(f) A new layer of silicon oxide is applied. The entire process of photo resist, mask, light exposure, and etching is repeated to expose new areas of the substrate.

(g) A second layer of wiring is now formed by a second metallization process, photo resist, masking and etching.

(h) With the circuit now complete, the disc or wafer is sliced up into the individual ICs. Recall that 300 or more ICs can be made on one wafer.

(i) Wires are connected to each of the ICs, they are packaged and then tested.

The above process can produce 300 to 600 semiconductor devices or complex integrated circuits from a single slice. Of course, the control of temperature, the accuracy of masking and so on must be carefully done and the automatic equipment required to perform this process costs millions of dollars.

TRANSISTOR BIASING

The most common application for a transistor is that of an AMPLIFIER. An amplifier accepts a low level current or voltage at its input and delivers a higher level current or voltage at its output terminals.

In order for a transistor to function properly as an amplifier the Base-Emitter junction must be FORWARD biased to conduct electrons. This is accomplished by the positive voltage, V_B, as shown in Figure 14 (b) and (c). The Collector-Base junction must be REVERSE biased (non-conducting) and this is done by the V_{CC} voltage source, also shown in Figures 14(a), 14(b) and (c).

TRANSISTOR OPERATION

The basic operation of the transistor is illustrated in Figure 14 where the transistor is considered to act as a "valve" for electron flow.

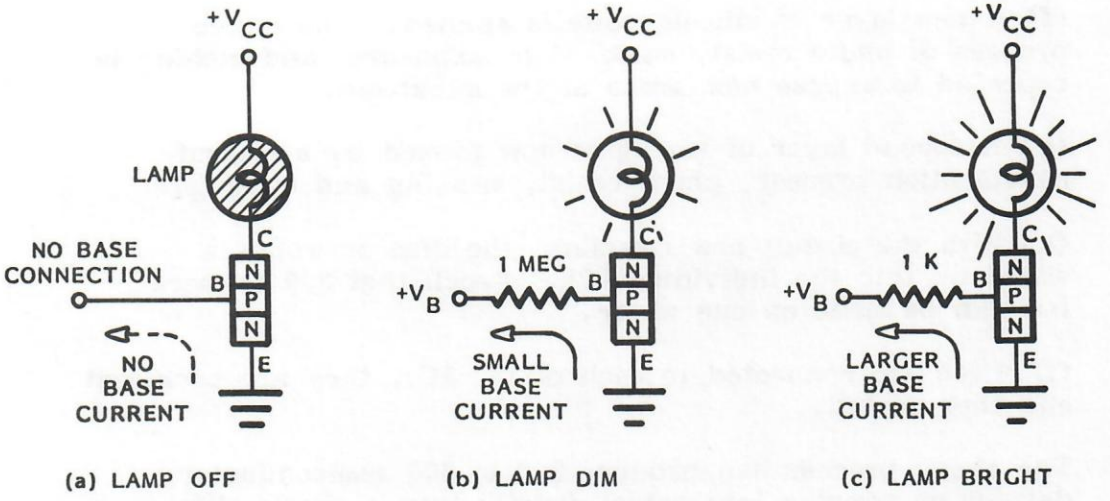


Figure 14 - Transistor as a current valve.

By creating a small current flow from the emitter to the base, a much larger current flows from the emitter to the collector. In Figure 14(a) with an open base circuit, there is no base current and thus no collector current. In Figure 14(b), with a small base current, enough collector current flows so that the lamp glows dimly. In Figure 14(c), the base resistance is smaller (1K) and so the increased base current causes a larger collector current flow and the lamp in the collector circuit glows brightly.

The process within the transistor that allows the small base current to control the larger collector current is shown in Figure 15 and explained below.

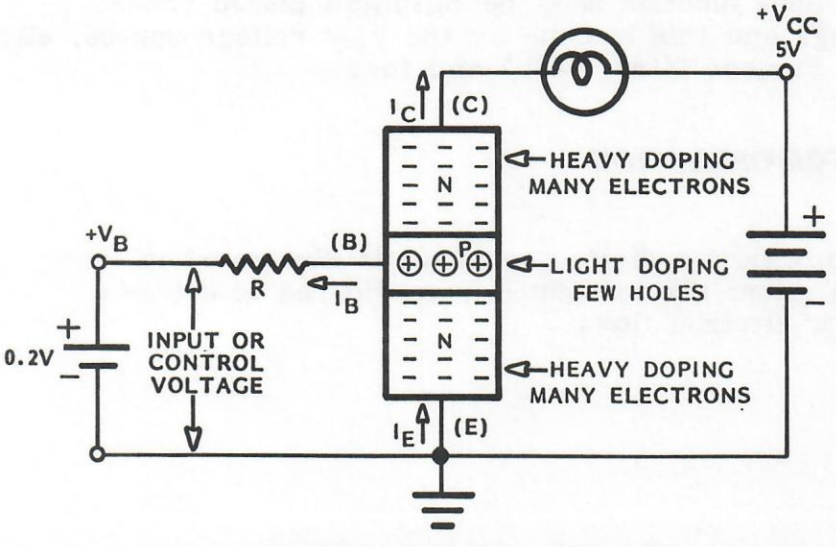


Figure 15 - Transistor operation.

The center base material (Figure 15) is very thin, often as little as 0.8 microns which is approximately 0.00003 inches (or 3 - 100,000 inches). In addition, the P-type base section is very lightly doped so there are very few holes compared to the many electrons in the N-type sections of the emitter and collector.

Consider that the input or control voltage at the base, V_B, is + 0.2 volts. The diode consisting of the base (P-type) and emitter (N-type) is forward biased but there is no current flow because the applied voltage does not exceed the junction barrier potential of the diode, 0.7 volts for silicon and 0.3 volts for germanium. The barrier potential must be exceed before current will flow.

The collector to base diode is reverse biased because the P-type base section is at a lower potential than the N-type collector. Thus, no current flows in the collector circuit or the base circuit. The transistor is in the off condition and the lamp in the collector does not light.

Now let us increase the input voltage, V_B in Figure 15, to a value greater than 0.7 volts so that the base-emitter junction is forward biased and conducts. A large number of electrons from the N-type emitter flow into the P-type base. These electrons fill the positive holes in the base and result in a base current flow through the base circuit resistor (R), to $+V_B$ as in any forward biased diode. But, because the base section is so thin and so lightly doped, very few electrons can combine with the few holes in the base section resulting in a low base "input" current. The remaining electrons from the emitter, continue through the very thin base section to the collector because the negative charged electrons are attracted by the positive voltage at the collector from the $+V_{CC}$ source. These electrons, flowing from the emitter to the collector, provide a high "output" collector current.

The current distribution in the transistor can be expressed using Kirchhoff's Current Law simply as:

$$I_E = I_B + I_C$$

This can be transposed to:

$$I_B = I_E - I_C \text{ and } I_C = I_E - I_B$$

These simple relationships clearly indicate the flow of current in the transistor and are useful in later studies.

CURRENT GAIN

The current gain in any circuit is defined as the ratio of the output current to the input current and is expressed as:

$$\text{CURRENT GAIN} = \frac{I_{out}}{I_{in}}$$

For the circuits shown in Figures 14 and 15, the input current is the base current I_B and the output current is the collector current, I_C. Thus, the current gain for the transistor amplifier circuits may be expressed as:

$$\text{TRANSISTOR CURRENT GAIN} = \frac{I_C}{I_B}$$

The current gain of the transistor circuit, where the input is applied to the base and the output is taken from the collector, is defined by the Greek letter BETA, β. Because we are measuring the dc values of I_B and I_C, the gain is called the dc beta and is expressed as:

DC CURRENT GAIN (BETA)	$\beta_{dc} = \frac{I_C}{I_B}$

The dc current gain, beta dc, of the circuit of Figure 15 is also defined by the letters H_{fe}, pronounced "H sub f e." The letter H stands for "Hybrid" which indicates a special system used to denote measurements of the transistor operation. The letter "f" indicates that it is the measurement of the forward current gain. The letter "e" stands for the emitter, the element that is common to both the input and output circuits. When the letter H is capitalized it indicates the dc current gain but some texts will show the dc current gain as h_{FE}. When all the letters are lower case, h_{fe}, it indicates the ac signal current gain. This method of indicating current gain is explained in greater detail in Information Sheet 3, Transistor Models. Other current gains are also defined later.

If, in the circuit of Figure 10, the base current is 10 μA and the resulting collector current is 2 mA then we define the current gain as:

$$\beta_{dc} = H_{fe} = \frac{I_C}{I_B}$$

$$= \frac{2 \text{ mA}}{10 \ \mu\text{A}} = \frac{2000 \ \mu\text{A}}{10 \ \mu\text{A}}$$

$$\boxed{\beta_{dc} = 200}$$

Because we are able to obtain a high current output from a low current input, the transistor device is a very powerful control valve for electricity. The transistor is also referred to as a "current operated device" and is the basis for all modern electronics such as integrated circuits (ICs), industrial controls, computers and other high technology systems as covered throughout the entire study of electronics.

CONCLUSIONS

We have learned from this information sheet that:

1. A semiconductor material has an ability to conduct electricity that falls between conductors and insulators.

2. When a PN junction is formed, a "barrier potential" is developed due to a brief migration of electrons across the junction from the N to P areas. We must apply a voltage to overcome this potential before current flows across the PN junction.

3. The PN junction forms a diode that will conduct a current flow in one direction only.

4. A bipolar junction transistor or BJT is formed from a PNP or NPN sequence of semiconductor materials.

5. The base section of the transistor is less than a micron thick and is lightly doped. Thus there are very few current carriers in the base which results in a low base current.

6. Over 98% of the emitter current flows to the collector with only a small amount flowing off as base current.

7. The current relationship between the three elements of the transistor, B, E and C is expressed as:

$$I_E = I_B + I_C \qquad I_B = I_E - I_C \qquad I_C = I_E - I_B$$

8. The current gain of the transistor circuit, where the emitter is grounded (so that it is common to both the input and output circuits) is called beta (β_{dc}), or H_{fe}.

9. Beta is calculated from:

$$\beta_{dc} = \frac{I_C}{I_B}$$

KEY TERMS

1. ALLOY TRANSISTOR

   The fabrication of transistor using the alloy process. Also called a fused junction, it is created by alloying the impurity on the semiconductor substrate and heating to the melting point. The impurities alloy with the base substrate and form N and P areas.

2. BARRIER POTENTIAL

   A voltage developed across a PN junction. It is 0.3 volts for a germanium junction and 0.7 volts for a silicon junction.

3. BASE

   In a transitor, it is the element positioned between the emitter and collector. Varying the base current varies and controls the collector current.

4. BETA dc

   The ratio of dc collector current to dc base current. It is typically between 90 and 300 or more and is expressed as:

   $$\beta_{dc} = I_C / I_B$$

5. CHIP

   A very small piece of semiconductor material, cut from a wafer, on which electronic components and circuits are formed.

6. COLLECTOR

   The electrode in a transistor that attracts or collects the electrons from the base region that have not recombined in the base region.

7. CONDUCTOR

   A material that conducts an electrical current through the movement of free electrons. A conductor has a very low resistance.

8. CRUCIBLE

A vessel or container used to heat substances to a high temperature.

9. CURRENT CARRIERS

In N-type material the current carriers are electrons. In P-type material the current carriers are holes. The current carriers allow an electrical flow through solid conductors and semiconductors.

10. CURRENT GAIN

The ratio of the output current to the input current of a transistor circuit expressed as:

$$\text{Current Gain} = A_i = \frac{I_{out}}{I_{in}}$$

11. DIFFUSION

A process used to impregnate semiconductor materials with impurity donor or acceptor atoms.

12. DIODE

A two electrode semiconductor device, called a PN junction, that allows a current flow through it in one direction only, from N to P.

13. DIP IC HOUSING

Dual In-Line package used to encase integrated circuit chips.

14. DOPING

The addition of P-type and N-type impurities, in carefully controlled amounts, to pure silicon or germanium to create N-type and P-type materials. These materials are used to make diodes, bipolar transistors and many other semiconductor devices.

15. EMITTER

The electrode in the transistor which generates the current carriers that flow into the base area and on to the collector circuit.

16. FLAT PACK

An integrated circuit mounted in a flat, thin, square housing with the connecting wires projecting from 2, 3 or 4 sides.

17. FORWARD BIAS

A voltage applied across a semiconductor junction so as to cause conduction. The positive voltage terminal is connected to the P-type material and the negative voltage terminal is connected to the N-type material thus cancelling the barrier potential to cause conduction.

18. GROWN CRYSTAL

A method of growing a single crystal ingot by rotating and pulling a seed crystal from the molten semiconductor material.

19. H_{fe}

The dc current gain of a transistor in a circuit where the emitter is the common element. H_{fe} is equal to β_{dc}.

20. I_B; I_C; I_E

I_B represents the transitor base current; I_C is the transistor collector current; I_E is the transitor emitter current.

21. INSULATOR

A material in which the atom's valence electrons are tightly held thus providing little or no free electrons for conduction. The insulating material is used to separate conductors to prevent undesired current paths.

22. INTEGRATED CIRCUIT (IC)

A complete, inseparable, electronic circuit made on a small semiconductor substrate. The substrate is mounted in a housing to allow connections to be made to the IC.

23. LARGE SCALE INTEGRATION (LSI)

Fabrication of an IC with 100 or more circuits.

24. MASK

A device that is placed on the substrate to prevent a process from acting upon certain areas of the substrate.

25. MEDIUM SCALE INTEGRATION (MSI)

Fabrication of an IC with more than 10 circuits but less than 100 circuits.

26. PN JUNCTION

The region of change between the P and N areas of a semiconductor. The term, PN Junction, is used to define a diode which consists of P and N material with a single junction.

27. PHOTORESIST

A solution that hardens when exposed to ultra-violet light and then resists etching acids.

28. PLANAR TRANSISTOR

Diffused junction transistors in which the emitter, base and collectors are all on the same plane surface of the substrate.

29. REVERSE BIAS

A voltage applied across a semiconductor junction so as to prevent conduction. The positive voltage terminal is connected to the N-type material and the negative voltage terminal is connected to the P-type material. This reinforces the barrier potential, preventing conduction.

30. SEED CRYSTAL

The starter crystal which is immersed in the molten silicon, rotated and pulled out. It is around the seed crystal that the new crystal ingot is grown.

31. SEMICONDUCTOR

A material whose resistance falls between that of a conductor and an insulator. A typical conductor has one valence electron; a typical insulator has eight valence electrons while a semiconductor has four valence electrons.

32. SILICON OXIDE

A substance created when silicon and oxygen are chemically combined. Silicon oxide is a form of glass and acts as an insulator.

33. SMALL SCALE INTEGRATION (SSI)

Fabrication of an IC with 10 or fewer circuits.

34. SUBSTRATE

The base on which integrated circuits components are formed.

35. TRANSISTOR

A semiconductor device, made in an NPN or PNP sequence, that can amplify voltage, current or power.

ASSIGNMENT

Answer the following multiple choice questions.

1. In electronics, a passive device is defined as one that:

   a. does not move.
   b. amplifies.
   c. does not amplify.
   d. none of the above.

2. In electronics, an active device is one that:

   a. moves.
   b. amplifies.
   c. does not amplify.
   d. none of the above.

3. Which of the following may be classified as active devices?

   a. Transistors.
   b. FETs.
   c. Vacuum Tubes.
   d. all of the above.

4. A semiconductor material valence ring contains approximately:

   a. 1 electron.
   b. 2 electrons.
   c. 4 electrons.
   d. 8 electrons.

5. When a PN junction is formed, electrons:

   a. move from the N to P areas.
   b. fill some holes in the P area.
   c. by moving, create a barrier potential.
   d. all of the above.

6. The barrier potential developed across a silicon PN junction is:

   a. 0.7 volts.
   b. 0.485 volts.
   c. 0.3 volts.
   d. any of the above.

7. When a transistor is used as an amplifier, the B-E junction is _____ biased and the B-C junction is _____ biased.

   a. forward; forward
   b. forward; reverse
   c. reverse; forward
   d. reverse; reverse

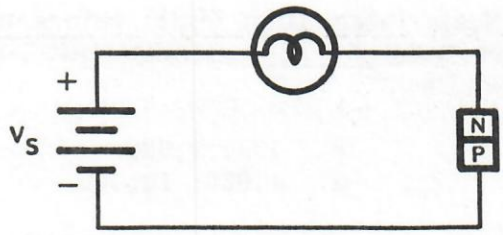


Figure 16 above refers to question 8.

8. In the circuit of Figure 16, the lamp will:

   a. not light.
   b. light dimly.
   c. light brighter than when connected directly to V_S.
   d. light almost as brightly as when connected to V_S.

9. A transistor may be defined as:

   a. an active device.
   b. a three terminal device.
   c. having a PNP or NPN sequence.
   d. all of the above.

10. In a transistor amplifier circuit, a:

   a. small collector current generates a large base current.
   b. large collector current causes a small base current.
   c. small base current controls a large collector current.
   d. none of the above.

11. The current gain of a transistor amplifier is defined as:

   a. I_C/I_B.
   b. beta.
   c. H_{fe}.
   d. all of the above.

12. When manufacturing ICs, silicon oxide is used as a (an):

   a. insulating material.
   b. N-type dopant.
   c. P-type dopant.
   d. contact material.

13. The term Medium Scale Integration (MSI) refers to an IC that contains more than _____ circuits but less than _____ circuits.

   a. 1; 10
   b. 10; 100
   c. 100; 1,000
   d. 1,000; 10,000

14. The term Large Scale Integration (LSI) refers to an IC that contains more than _____ circuits but less than _____ circuits.

a. 1; 10
b. 10; 100
c. 100; 1,000
d. 1,000; 10,000

15. Given a collector current of 3 mA and an emitter current of 3.05 mA, the base current is:

a. 50 μA.
b. 2.95 μA.
c. 150 μA.
d. none of the above.

16. Given a base current of 20 μA and a collector current of 3 mA:

a. $\beta = 150$.
b. $H_{fe} = 150$.
c. $I_E = 3.02$ mA.
d. all of the above.

17. When constructing a bipolar transistor, the thinnest of the three sections is always the:

a. base.
b. emitter.
c. collector.
d. they are all equal.

Figure 17 above refers to question 18.

18. In Figure 17, (a) and (b) are the schematic symbols for junction transistors. They represent:

a. PNP (a) and NPN (b).
b. NPN (a) and PNP (b).
c. NPN (a) and NPN (b).
d. PNP (a) and PNP (b).

Transistor Testing Methods

Lesson No. 1

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 1.

2. Bipolar transistors consist of three alternate sections of P and N materials. The resultant construction contains two junctions that can be tested as ordinary diodes using standard meters.

3. The physical packaging and terminal connections for transistors are illustrated.

DISCUSSION

It is possible for transistors that are used in an operating circuit to fail causing the circuit to operate improperly or not operate at all. The most common transistor failures are due to open or shorted junctions. A defective transistor may be tested by the procedure outlined in this lesson and performed in Experiment No. 1.

An explanation of semiconductors and transistor operation was presented in the preceding Information Sheet 1, Unit J1, Bipolar Transistors. In our experiments, we will study the transistor in practical operating circuits. The transistor in Figure 1 is wired in a circuit where the base-emitter junction must be forward biased, resulting in a current which is the "input" to the transistor. The base-collector junction must be reverse biased and no current flows from the base input lead out to the collector. The output current flows from the emitter to the collector.

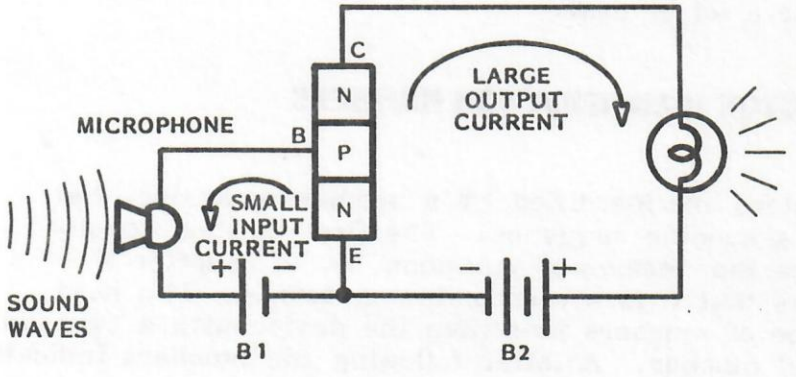


Figure 1 - Transistor amplifier circuit.

As illustrated in Figure 1, the transistor is wired into a circuit where the small input current controls an output current which can be 100 to 200 times larger. The small input current, typically 50 μA, controls the output current, up to typically 100 mA which lights the lamp in the collector circuit. The amplified output current of 100 mA is supplied by the battery or voltage source, B2. The input current is supplied by battery B1 and can be controlled by any device such as the microphone, as shown, a photocell as in an earlier experiment or by a radio signal picked up by an antenna.

The experiment that follows this lesson has three parts. First, we will use the transistor in a circuit similar to that in Figure 1 to show how we can control the output current by varying the base current. Then we will check several transistors by testing their diode junctions using the methods to be described in this lesson. Finally, we will examine various types of transistor packages and identify their lead connections.

TRANSISTOR PACKAGING AND TERMINALS

Transistors have three connecting terminals, the base, emitter and collector, and are packaged in a variety of enclosures or CASES. Some typical transistor cases are shown in Figure 2. The shapes of the cases are referred to as "Transistor Outlines," abbreviated TO. Each case shape is given to TO number and the base, emitter and collector connections are marked on the TO drawing.

The TO-92 outline in Figure 2 is shown twice in (a) and (b), each using a different lead arrangement. The TO-220 and TO-3 cases (e) are very large compared to the others because they are used in high power circuits so the transistors must dissipate a lot of heat.

TRANSISTOR IDENTIFICATION NUMBERS

Transistors are identified by a numbering system that follows a specific sequence. The first number usually indicates the number of junctions, 2. The letter N indicates that it is a semiconductor device. The next sequence of numbers identifies the device with a type number or model number. A letter following the numbers indicates

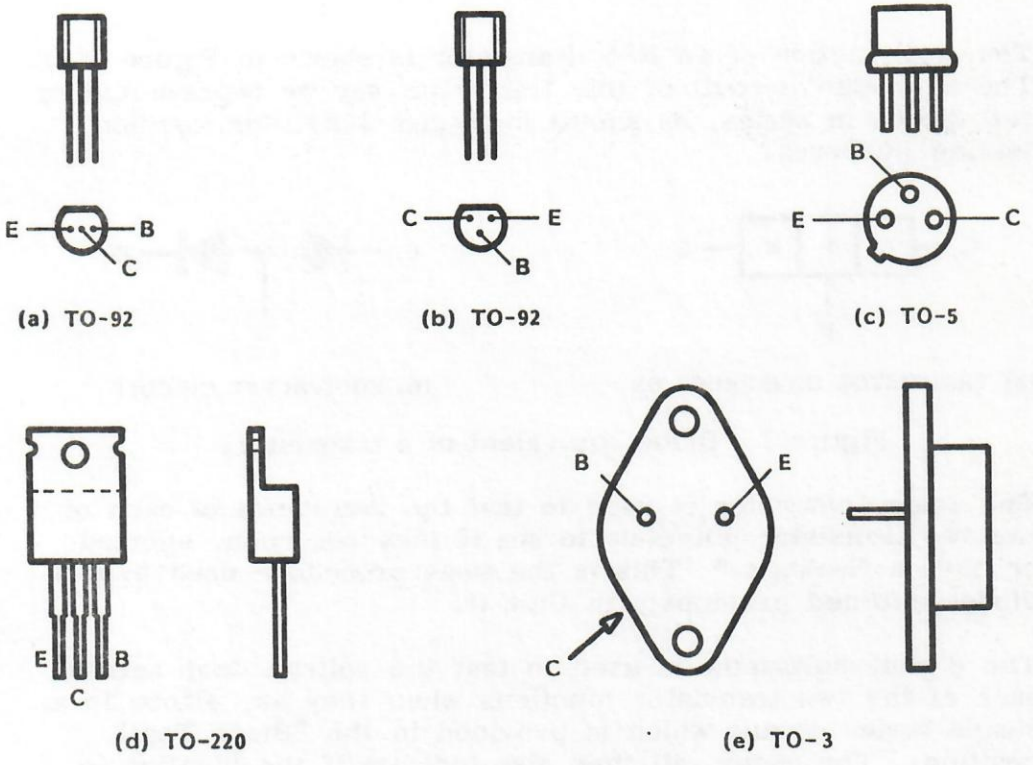


Figure 2 - Typical transistor case outlines (TO).

an improvement or modification of the original transistor. Thus, for a 2N1572A transistor, you know that the:

2N, indicates a two junction semiconductor device

1572, indicates the type or model number of the transistor, and

A, is the first modification or improvement of the original 2N1572.

TRANSISTOR TESTING

There are several methods of testing transistors. When we use a special test instrument called a "Transistor Tester," it not only indicates if the transistor is "good," but it also indicates how much it will amplify current. The transistor may also be checked using an analog ohmmeter or multimeter, a digital VOM multimeter with a Diode Test function and it may be tested using a low voltage source and a voltmeter.

The construction of an NPN transistor is shown in Figure 3(a). The equivalent circuit of this transistor may be represented as two diodes in series, as shown in Figure 3(b), for junction testing purposes.

(a) TRANSISTOR CONSTRUCTION (b) EQUIVALENT CIRCUIT

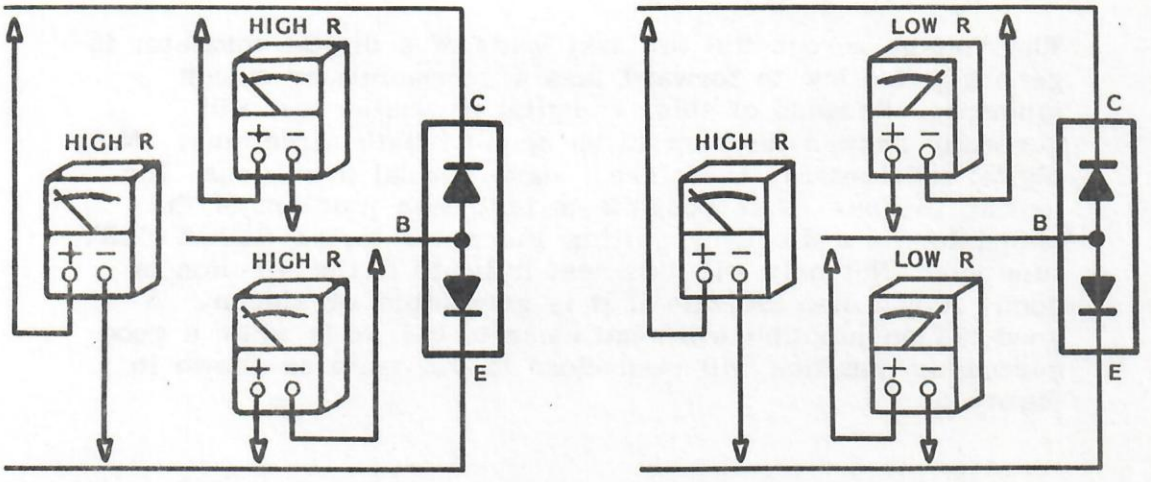
Figure 3 - Diode equivalent of a transistor.

The analog ohmmeter is used to test the resistance of each of the two transistor junctions to see if they are open, shorted or have a "leakage." This is the same procedure used to test diodes outlined previously in Unit H.

The digital multimeter is used to test the voltage drop across each of the two transistor junctions when they are placed in a simple series circuit which is provided in the "Diode Test" position. The meter will then also indicate if the junction is open, shorted or has leakage. The digital multimeter can also indicate if the junction under test is germanium or silicon by the amount of voltage dropped across it.

TESTING WITH AN ANALOG OHMMETER

Each of the transistor junctions, similar to diode junctions, may be tested for shorts, opens or leakage using an analog ohmmeter as shown in Figure 4. The internal battery of the ohmmeter acts as the voltage source to forward or reverse bias the transistor base-emitter or base-collector junctions as shown. In Figure 4(a), the junctions are reverse biased by the internal ohmmeter battery and the resistance readings from E to B and from B to C will be very high (close to infinite). The reading from C to E will also be very high because, although the polarity is correct to forward bias the E to B junction, the C to B junction is reverse biased and, since the junctions are in series, the ohmmeter reads high.



ALL OHMMETER READINGS ARE HIGH

(a) OHMMETER REVERSE BIASES JUNCTIONS

BOTH JUNCTION READINGS ARE LOW

(b) OHMMETER FORWARD BIASES JUNCTIONS

Figure 4 - Transistor junction tests with analog ohmmeter.

When the junctions are forward biased by the ohmmeter's internal battery as in Figure 4(b), the resistance readings will be low, between 80 to 150 ohms on the R x 1, R x 10 or the R x 100 scale of a typical analog ohmmeter. The reading of the ohmmeter connected from C to E, however, will still read infinite resistance because now the C to B junction is reverse biased.

If either of the two junctions of a transistor indicate a low resistance in both directions, the conclusion is that the junction is SHORTED and defective. If either of the two junctions indicate a high resistance in both directions, then the conclusion is that the junction is OPEN and is defective. If an ohmmeter connected to read resistance from C to E of a transistor, shows a low resistance reading, the transistor is defective except where the particular ohmmeter circuit and range used has an internal voltage high enough to "turn on" a transistor and cause a low resistance reading. This happens particularly with germanium transistors because of leakage and will be reviewed later.

It is also possible for all resistance readings across the transistor terminals to be correct and yet the transistor might not function in a circuit. The most accurate test is one that also tests the transistor's ability to amplify.

TESTING WITH A DIGITAL VOM MULTIMETER

The voltage across the two test leads of a digital ohmmeter is generally too low to forward bias a germanium or silicon junction. Because of this, a digital ohmmeter test will generally show a junction to be open in both directions. Many digital multimeters, therefore, have special provisions for testing diodes. It is possible to test each junction of the transistor as a diode by setting the meter to the DIODE TEST function. Not only will this test indicate if the junction is good, it will also indicate if it is germanium or silicon. A good silicon junction will read close to 0.7 volts while a good germanium junction will read close to 0.3 volts as shown in Figure 5.

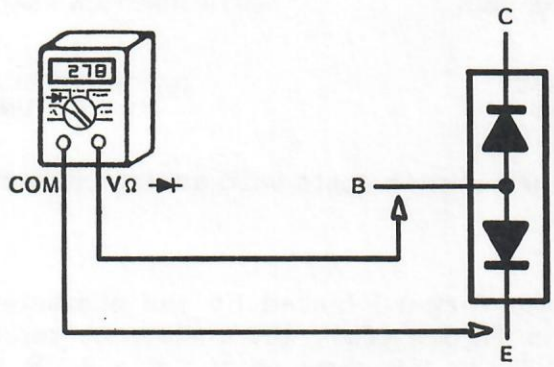
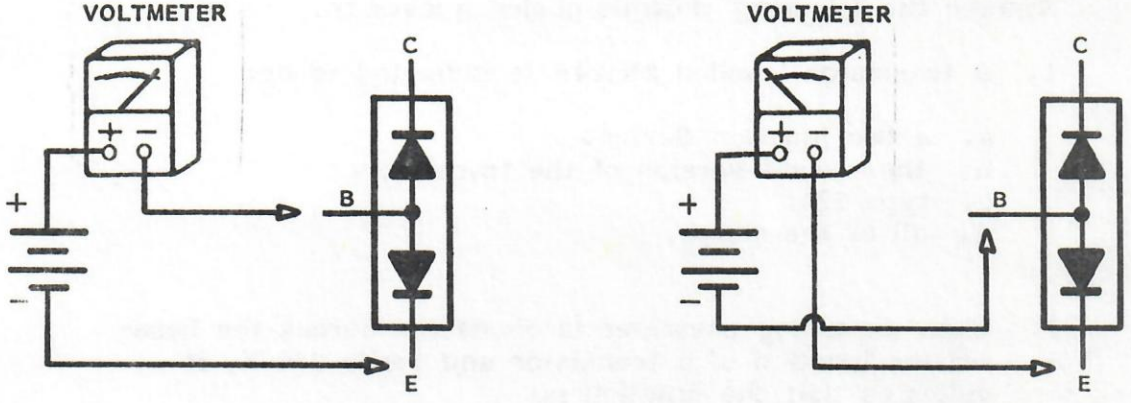


Figure 5 - Testing a transistor junction with a Digital Multimeter set for a Diode Test.

TESTING WITH A VOLTAGE AND VOLTMETER

Transistor junctions may also be tested using a voltage source and a voltmeter as shown in Figure 6. When the junction is forward biased, as in Figure 6(a), the meter will read the 5 volt source less the voltage drop across the junction.



(a) FORWARD BIAS TEST

(b) REVERSE BIAS TEST

Figure 6 - Testing a transistor junction with a voltage source and voltmeter.

The reverse bias test in Figure 6(b) will show a voltage reading only if the junction has a "leakage current." Some small amount of leakage is normal for a germanium junction. A typical reverse bias leakage voltage reading, using a 5 volt source, would be 0.05 to 0.1 volts for a germanium junction.

ASSIGNMENT

Answer the following multiple choice questions.

1. A transistor labelled 2N124A is indicated to be:

   a. a two junction device.
   b. the second version of the transistor.
   c. type 124.
   d. all of the above.

2. When an analog ohmmeter is connected across the base-emitter junction of a transistor and reads 250 K, it indicates that the junction is:

   a. reverse biased.
   b. forward biased.
   c. shorted.
   d. none of the above.

3. A transistor can be formed by a sequence of:

   a. P,N,P type silicon.
   b. N,P,N type germanium.
   c. either a or b.
   d. neither a nor b.

4. A transistor may be tested using a(an):

   a. analog ohmmeter.
   b. voltmeter and voltage source.
   c. digital multimeter with a Diode Test function.
   d. all of the above.

5. When testing a transistor with an analog ohmmeter, the transistor may be assumed to be the equivalent of:

   a. two diodes back-to-back.
   b. two diodes in series aiding.
   c. a field effect transistor.
   d. a vacuum tube.

Transistor Testing 1

OBJECTIVES

When you finish this experiment you will be able to:

1. Test NPN and PNP transistors with an Analog Ohmmeter.
2. Determine if a transistor is Silicon or Germanium by measuring the forward voltage drop across one junction.
3. Test NPN and PNP transistors with a Digital VOM.
4. Test transistors with a voltage source and voltmeter as on the Ed-Lab trainer panel.

REFERENCES

CES Lesson J1-1, Transistor Testing Methods

ADDITIONAL EQUIPMENT REQUIRED

a. Analog Volt-Ohmmeter
b. Digital Volt-Ohmmeter (Optional)
c. Transistors or Transistor Component Card (Optional)

BACKGROUND

1. The transistor has a current gain whereby a low current applied to the base input circuit can control a high current in the collector output circuit as will be demonstrated.
2. Standard Analog Meters or Digital Meters can be used to test the transistor junctions.
3. Transistor outlines are identified as are the location of the base, emitter and collector terminals.
4. This experiment is in five parts:

    1.1 Lamp Current Transistor Control
    1.2 Transistor Testing with Analog Ohmmeter
    1.3 Transistor Testing with Digital Meter (Optional)
    1.4 Transistor Testing with a Voltage Source
    1.5 Identifying and Testing Transistors (Optional)

PROCEDURE

1.1 LAMP CURRENT TRANSISTOR CONTROL

In this first part of the experiment, we will observe that the basic concept of a transistor circuit is that of a current amplifier where a small input "base" current controls a large output "collector" current. This is demonstrated in the circuit of Figure 1 where a small current flow through the resistance of your body, typically in microamperes, will control a larger current through a lamp.

1. Assemble the circuit shown in Figure 1.

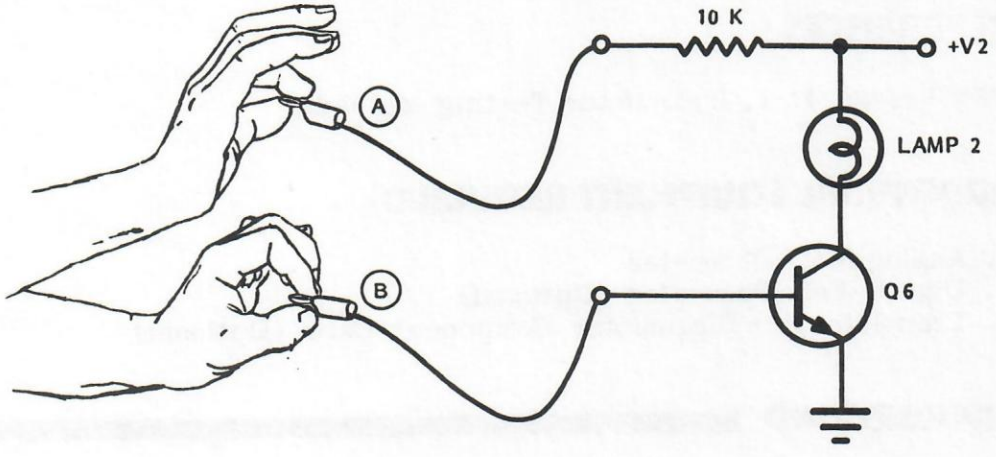


Figure 1 - Current amplifier EXPERIMENT.

2. With leads A and B "open," no base current flows and so no collector current flows. Thus, the lamp remains OFF.

   Grasp plugs A and B tightly between the thumb and forefinger of each hand. Your body resistance between your hands, when dry, will be high and can run from 2 to 5 megohms. This may not provide enough base current to turn the lamp ON.

   You may have to moisten your fingertips and grasp leads A and B. What happens?

   _____

   _____

   _____

3. Squeeze the A and B leads with differing pressure to change the contact resistance. How does this affect the lamp intensity?

_____

_____

_____

4. In the above test, you connected 9 volts (+V2) across your body resistance, in series with the base-emitter INPUT junction. This is a HIGH RESISTANCE path and the input current flow is small.

   The same 9 volts is connected across the lamp in series with the collector to emitter OUTPUT part of the transistor. The 9 volt source sees the lamp as a LOW RESISTANCE path and the high output current from the transistor flows to light the lamp.

   Because the same supply voltage is applied to the input through a HIGH RESISTANCE and to the output with a LOW RESISTANCE circuit, when this semiconductor device was invented, it was referred to as a:

TRANSFER - RESISTOR

   The first five letters of TRANSFER and the last five letters of RESISTOR were then combined to result in one shorter name which we now use; the:

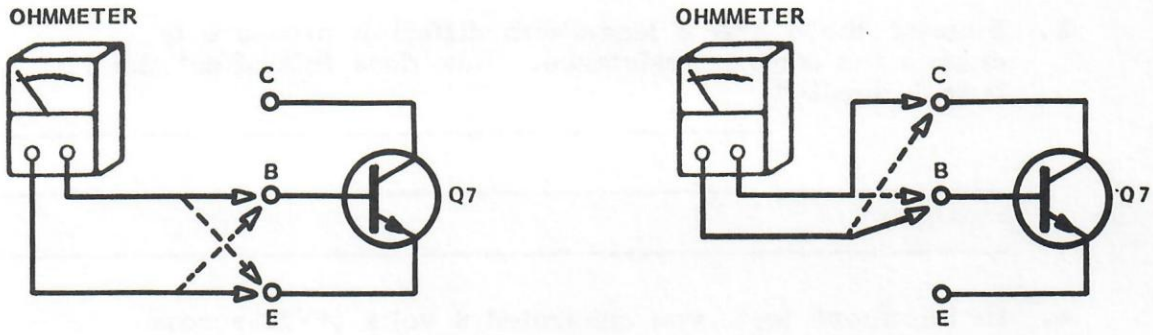
TRANSISTOR

You may conclude from the above that the transistor base current, while very low, can control the very high collector current. This sensitive variation in control was demonstrated when you varied your finger pressure on the base leads.

1.2 TRANSISTOR TESTING WITH ANALOG OHMMETER

We will now use an ANALOG VOM to test the junctions of two transistors mounted behind the trainer panel, one NPN and one PNP. We will later test external, loose transistors.

5. Set the analog ohmmeter to the R x 1 or R x 10 range. Zero adjust the ohmmeter. Refer to Figure 2.



(a) BASE-EMITTER JUNCTION (b) COLLECTOR-BASE JUNCTION

Figure 2 - Analog meter measurement EXPERIMENT.

Measure the forward and reverse resistances of the Base-Emitter junction of Q7, the NPN transistor mounted behind the trainer panel and record the readings below.

Q7 E-B JUNCTION RESISTANCES	R_{FWD} =
	R_{REV} =

6. Measure the forward and reverse resistances of the Collector-Base junction of transistor Q7 and record the readings below.

Q7 C-B JUNCTION RESISTANCES	R_{FWD} =
	R_{REV} =

7. Measure the resistance between the Collector and Emitter of Q7 with the ohmmeter positive lead to the collector and then with the negative lead to the collector. Enter both readings below.

+ C	R =
- C	R =

Does transistor Q7 test Good? _____

Does it show any junction leakage in the reverse direction?

_____

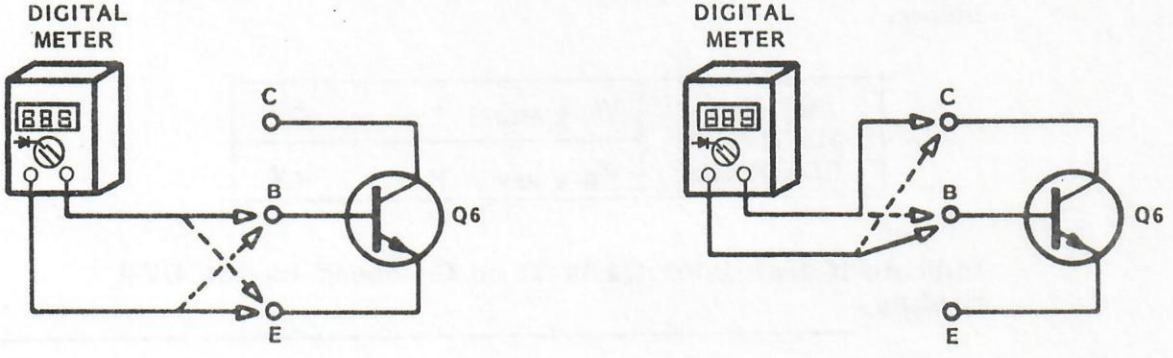
8. You may repeat the above procedure to test a PNP transistor, Q1, noticing that the only difference is that the junctions conduct when the polarities of the applied voltage are opposite to those used when testing the NPN transistor.

You can conclude from the above tests that both NPN and PNP transistors may be tested for shorts, open circuits and leakage, using an analog ohmmeter.

1.3 TRANSISTOR TESTING WITH DIGITAL METER (OPTIONAL)

In this part of the experiment we will use a DIGITAL VOM (DVM), that has a DIODE TEST function, to test each junction of a transistor on the Ed-Lab trainer panel. The Diode Test function of the meter will indicate if the transistor is silicon or germanium as well as indicating if a junction is shorted or open.

9. Use the Diode Test function of the Digital VOM to test the B-E junction of transistor Q6 by measuring the junction voltage drop as shown below. Record the meter indications for forward and reverse lead connections. Refer to Figure 3(a).



(a) BASE-EMITTER JUNCTION (b) COLLECTOR-BASE JUNCTION

Figure 3 - Digital meter measurement; EXPERIMENT

Q6 E-B JUNCTION READINGS	$V_{EB\ FWD}$ =	mV
	$V_{EB\ REV}$ =	mV

METER READING WITH LEADS OPEN	V_{OPEN} =	mV*

*READ NOTE ON FOLLOWING PAGE

*The reverse or "open" state reading on a DVM will vary for different meters. Some will read 1, others OL (for overload) and some a voltage value such as 1300 mV. What is the reading on your DVM when in the Diode Test function and the leads are not connected to the transistor?

DVM "OPEN" READING _____

Does the Q6 E-B junction voltage indicate a silicon or germanium transistor?

_____

10. Test the Q6 Collector-Base junction in both directions as shown in Figure 3(a) and enter the results below.

Q6 C-B JUNCTION READINGS	$V_{C\text{-}B\ FWD}$	=	mV
	$V_{C\text{-}B\ REV}$	=	mV*

*The reverse reading will vary as described in step 9.

11. Test the germanium transistor, Q4, B-E junction in the forward and reverse directions. Enter the readings below.

Q4 B-E JUNCTION READINGS	$V_{B\text{-}E\ FWD}$	=	mV
	$V_{B\text{-}E\ REV}$	=	mV

Indicate if transistor Q4 is Si or Ge based on the DVM reading.

_____

You can conclude from the above that the Diode Test function of a DVM can indicate the condition of both junctions in a transistor and also indicate if it is a silicon or germanium device under test.

1.4 TRANSISTOR TESTING WITH A VOLTAGE SOURCE

In this part of the experiment you will use a fixed low dc voltage source and a voltmeter, both on the Ed-Lab panel, to test the transistor junctions instead of using a multimeter.

12. Wire the circuit shown in Figure 4.

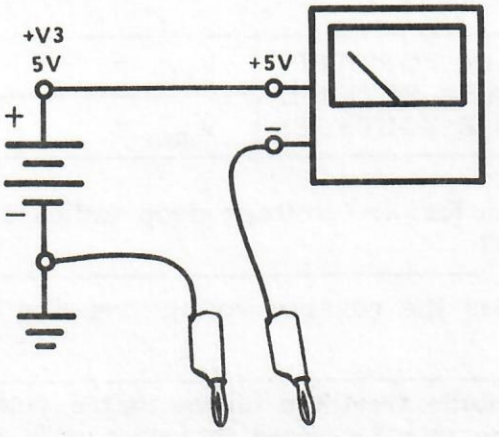


Figure 4 - Basic voltage test for transistor junctions; EXPERIMENT.

13. Connect the two loose leads, shown in Figure 4, together to produce a full-scale 5 volt reading on the meter. This indicates correct wiring. What is the meter reading?

_____

14. Connect the loose leads across the B-C junction of Q2 as shown in Figure 5 and then reverse the leads as also shown.

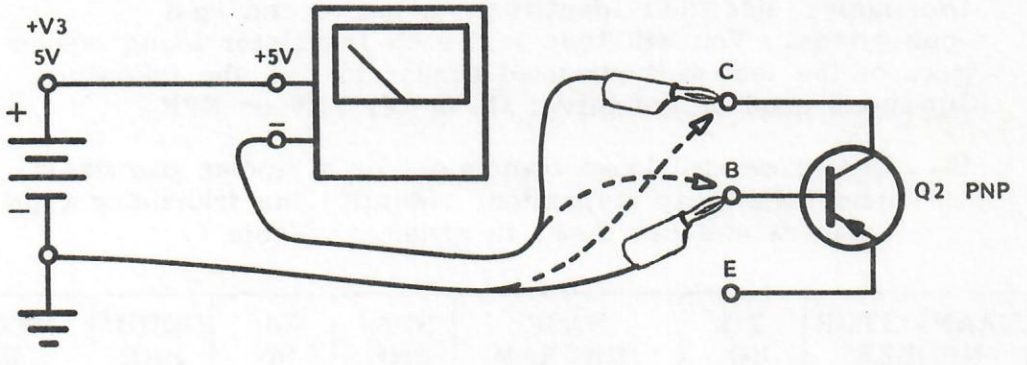


Figure 5 - Forward and reverse voltage test of a junction; EXPERIMENT.

Record the forward and reverse voltage readings below.

Q2 FORWARD AND REVERSE B-C VOLTAGES	V_{FWD} =	V
	V_{REV} =	V

Does the forward voltage drop indicate a Si or Ge junction?

_____

15. Connect the two leads to the B-E junction of transistor Q4, first in the forward direction and then in the reverse direction. Record the voltage readings below.

Q4 FORWARD AND REVERSE B-E VOLTAGES	V_{FWD} =	V
	V_{REV} =	V

Does the forward voltage drop indicate a Si or Ge junction? _____

What does the reverse voltage reading indicate? _____

_____

You can conclude from the above that a voltmeter and a voltage source may be wired in series with a transistor junction to check forward and reverse behavior. This method of testing can also indicate if the junction under test is Si or Ge by the voltage dropped across the junction which is equal to meter reading subtracted from the voltage source setting.

1.5 IDENTIFYING AND TESTING TRANSISTORS (OPTIONAL)

In this part of the experiment, you will examine actual loose transistors, list their identifying numbers and lead connections. You will then test each transistor using one or more of the test methods used earlier to find the following: Junctions good or defective; Ge or Si; PNP or NPN.

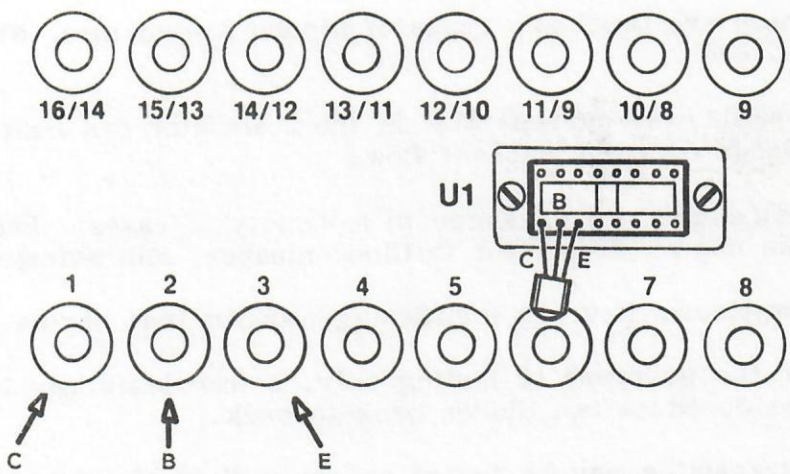
16. Obtain several loose transistors or a bipolar transistor card from your instructor. Identify the transistor type numbers and list them, in order, in Table 1.

TRANSISTOR NUMBER	TO NO.	BASE DIAGRAM	NPN/ PNP	Ge/ Si	GOOD/ BAD	METHODS USED
1.						
2.						
3.						
4.						

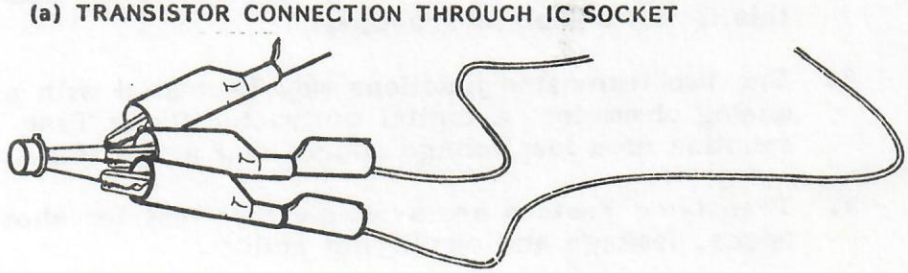
TABLE 1 - Test results on discrete transistors.

17. Determine the TO number for each listed transistor and enter the data in Table 1.

18. If loose transistors are used, they may be connected to the trainer as shown in Figure 6(a). The transistor leads are inserted into the first three connections of the IC socket and connection made to jacks 1, 2 and 3 alongside.



(a) TRANSISTOR CONNECTION THROUGH IC SOCKET



(b) TRANSISTOR CONNECTION USING ALLIGATOR CLIPS

Figure 6 - Methods of connecting to discrete transistors.

As shown in Figure 6(b), alligator clip adapters may be used to connect to loose transistors or transistors mounted on a board.

19. Determine if each transistor is NPN or PNP and if it is Ge or Si and enter the data in Table 1.

Determine the Good/Bad condition of each of the transistors using one of the methods described earlier and record the data in Table 1, indicating why you determined that a transistor was bad.

In this part of the experiment you have learned to recognize typical transistor outlines and identify the three connecting wires. You have also tested these transistors using one or more of the procedures outlined earlier.

CONCLUSIONS

We have learned from this experiment that:

1. There are two basic types of bipolar transistors, NPN and PNP.
2. A small base current flow in the transistor can control a large collector current flow.
3. Transistors are packaged in a variety of cases. Each case has a "Transistor Outline" number, abbreviated TO.
4. Transistors have an identifying number that begins with 2N.
5. For the purposes of testing only, a transistor may be considered as two diodes back-to-back.
6. A transistor may be tested as two individual diodes but this is not a foolproof method.
7. The two transistor junctions may be tested with an analog ohmmeter, a digital multimeter Diode Test function or a low voltage source and a voltmeter.
8. Transistor Testers are available that test for shorts, opens, leakage and amplifying ability.
9. A good silicon diode junction will read a low forward resistance and an infinite reverse resistance.
10. A good germanium diode junction will read a low forward resistance and a high but measurable reverse resistance.

KEY TERMS

1. ACTIVE DEVICE

   A circuit component that can provide an increased output (amplification) of voltage, current and/or power when used in conjuction with a power supply. Typical active devices are transistors and vacuum tubes.

2. AMPLIFIER

   A device or circuit that obtains its power from a source other than the input signal and provides a duplicate of the input at its output terminals. The output signal has its voltage level, current level and/or power level increased. The amount of signal increase is called the gain and is defined by the ratio of output to input which is expressed as A = output/input.

3. FORWARD BIAS

   A voltage applied across a semiconductor junction so as to cause conduction. The (+) voltage terminal is connected to the P material and the (-) voltage terminal is connected to the N material.

4. GERMANIUM

   A metallic substance that has semiconductor properties and is used for diodes and transistors. It develops a 0.3 volt drop across a forward biased junction.

5. NPN TRANSISTOR

   A transistor formed from a negative-positive-negative combination of semiconductor material.

6. PASSIVE DEVICE

   A circuit component or device that introduces a loss of voltage, current and/or power. Typical passive devices are resistors, capacitors, inductors and transformers.

7. PNP TRANSISTOR

A transistor formed from a positive-negative-positive sequence of semiconductor material.

8. REVERSE BIAS

A voltage applied across a semiconductor junction so as to prevent conduction. The (+) voltage is connected to the N material and the (-) voltage is connected to the P material.

9. SILICON (Si)

A metallic substance that has semiconductor properties and is used for diodes and transistors. It develops a 0.7 volt drop across a forward biased junction.

10. TRANSISTOR

A two junction semiconductor device with an NPN or PNP sequence made of Silicon or Germanium. It has three terminals, Collector, Base, Emitter and is capable of amplification. It is an active device.

ASSIGNMENT

Answer the following multiple choice questions.

1. A bipolar transistor may be tested using a (an):

   a. analog ohmmeter.
   b. transistor tester.
   c. DVOM on the Diode Test function.
   d. any of the above.

2. A bipolar transistor:

   a. is made in an NPN sequence.
   b. is made in a PNP sequence.
   c. can be tested as two individual diodes.
   d. all of the above.

Figure 7 above refers to questions 3 to 5.

3. The transistor symbols shown in Figure 7 are:

   a. NPN (a); PNP (b).
   b. PNP (a); NPN (b).
   c. both NPN types.
   d. both PNP types.

4. For the transistor symbols shown in Figure 7, the leads identified are:

   a. A-Collector; B-Emitter; C-Base.
   b. A-Emitter; B-Base; C-Collector.
   c. A-Base; B-Collector; C-Emitter.
   d. A-Collector; B-Base; C-Emitter.

5. An analog ohmmeter is set on the R x 1 scale and connected from E to C of transistor (a) in Figure 7. The reading will be:

   a. 100 ohms if E is minus and C is plus.
   b. 100 ohms in either direction.
   c. 100 ohms in one direction and 1K in the other direction.
   d. infinite in both directions.

6. It is possible to determine if a transistor is a Si or Ge type when testing it with an analog ohmmeter if:

   a. a voltmeter is also used to measure the junction voltage drop when forward biased.
   b. the forward - reverse resistance ratio is calculated (Ge low; Si high).
   c. the collector to emitter resistance is measured and it is very high for Si and moderate for Ge.
   d. all of the above.

Transistor Voltages

Lesson No. 2

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 2, Transistor Action.

2. The three transistor leads must be connected to the proper voltages for correct operation in a circuit.

3. The relationship between the currents in the transistor elements, base, emitter and collector, are defined as alpha (α) and beta (β), and will be used later in circuit study and design.

4. The transistor can operate in three modes or "regions." These are: Cut-off, Linear and Saturation. Analog amplifier circuits are operated in the linear region.

DISCUSSION

The second experiment demonstrates the basic operation of the transistor. The normal operation of a transistor as an amplifier requires that voltages be connected to the base, emitter and collector so that:

a. the base-emitter junction is forward biased.
b. the base-collector junction is reverse biased.

BIAS VOLTAGES

The basic method of forward biasing and reverse biasing the transistor junction is developed in Figure 1. The transistor is represented by the three sectioned block (N,P,N) biased by two voltage sources +V and -V. The -V source forward biases the base-emitter junction and the +V source reverse biases the base-collector junction.

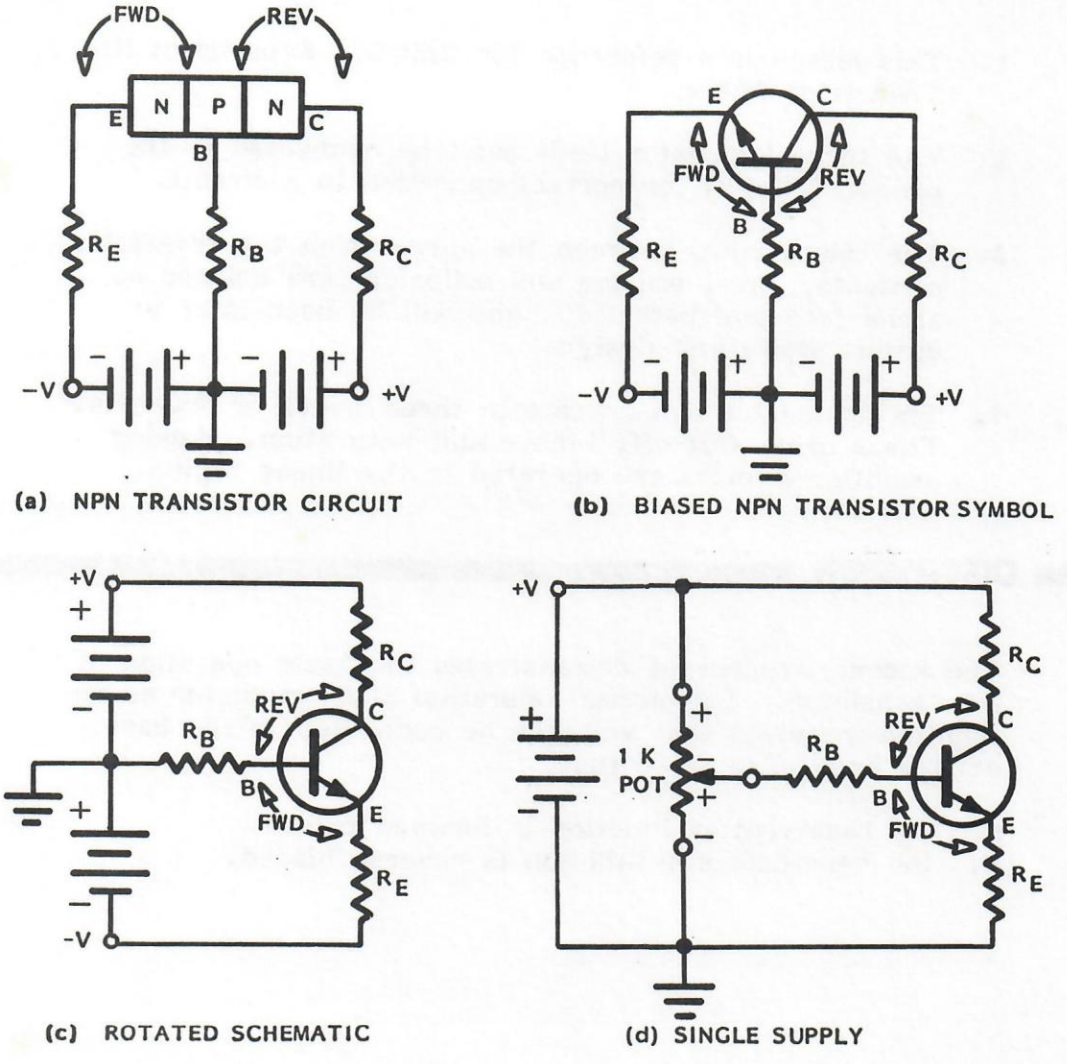


Figure 1 - Evolution of the basic transistor circuit.

This same circuit is redrawn in Figure 1(b) where the transistor circuit symbol is used instead of the block symbol. Figure 1(c) then shows the same circuit as (b) but rotated so that its appearance is closer to the standard method of drawing transistor circuits. The circuit shown in (c) is modified in (d) by replacing the two voltage sources, -V and +V, with a single voltage source, +V and a 1K potentiometer that acts as a voltage divider. The 1K pot can be considered as a two resistor voltage divider that provides both the voltages needed to bias the transistor.

CURRENT GAIN, BETA (β)

The transistor in Figure 2 is wired with the emitter connected to a common point with the two voltage sources. This is called a COMMON EMITTER configuration, abbreviated CE.

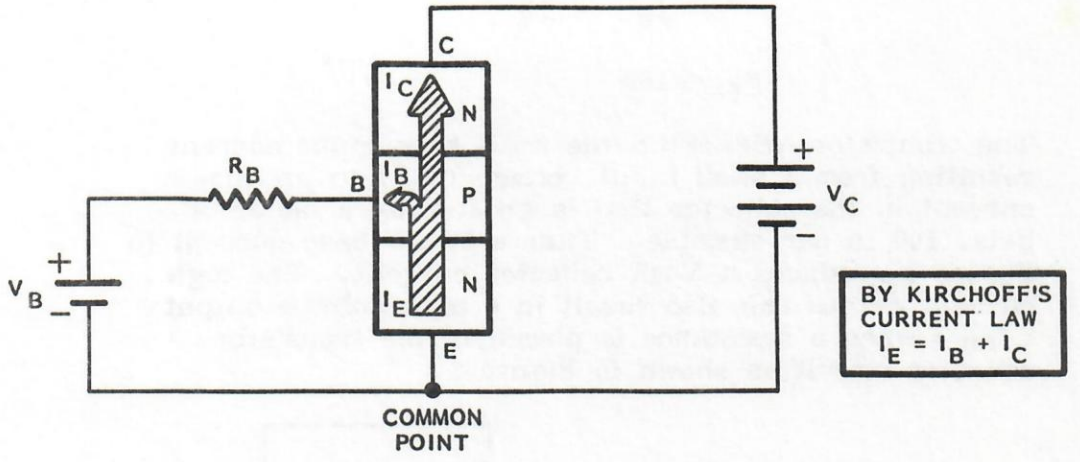


Figure 2 - Basic common emitter (CE) circuit.

With the base-emitter junction forward biased, the emitter current flows into the thin, lightly doped base area. A few of the electrons combine with the holes in the base area and flow off as base current. Most of the electrons flow through the base area into the collector where they flow off as collector current. This was explained earlier in Information Sheet 1, Unit J1.

The relationship or ratio of the collector and base dc currents for the circuit of Figure 2 was defined by the Greek letter beta (β) and is expressed as:

$$\beta_{dc} = \frac{I_C}{I_E} \qquad (1)$$

Beta is also referred to as H_{fe} where H stands for "hybrid," a system used to measure the transistor characteristics. The letter "f" stands for "forward current gain" and "e" stands for the emitter which is common to both the input and output. the hybrid system is reviewed in a later information sheet.

If, in the circuit of Figure 2, the base current is 50 μA and the collector current is 5 mA, then the current gain, beta is given by:

$$\beta_{dc} = \frac{I_C}{I_B} = \frac{5}{0.05}$$

$$\beta_{dc} = 100$$

The transistor AMPLIFIES the small base input current resulting from a small input voltage (V_{in}) to produce a current in the collector that is greater by a factor of beta, 100 in our example. Thus a 50 μA base current in Figure 2 produces a 5 mA collector current. The high current output can also result in a high voltage output (V_{out}) when a resistance is placed in the transistor collector circuit as shown in Figure 3.

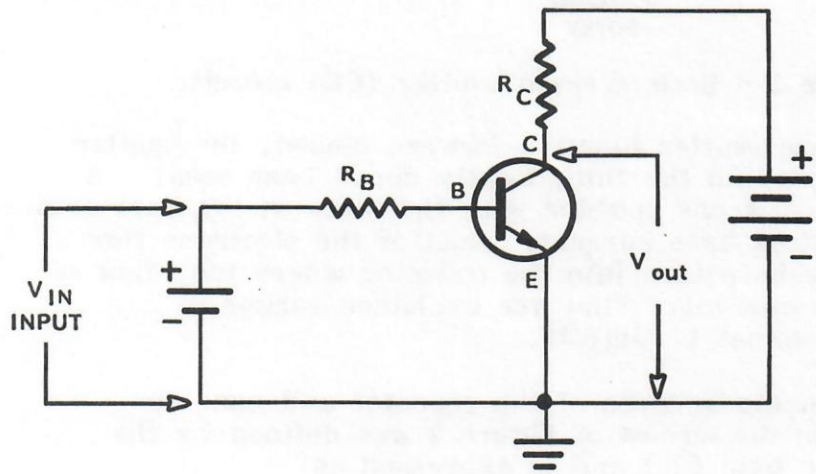


Figure 3 - Transistor used as a voltage amplifier.

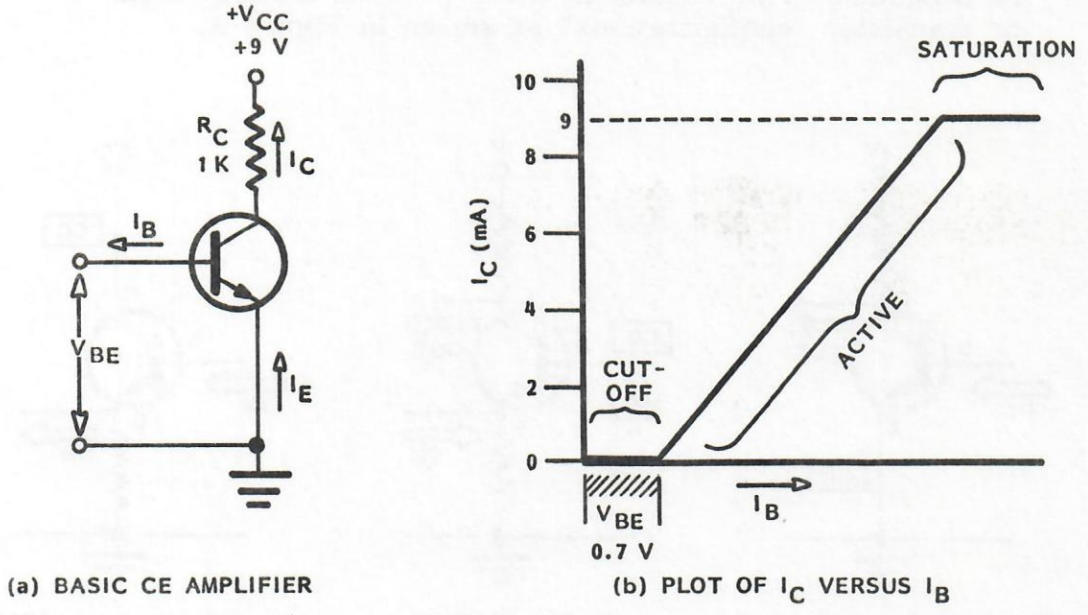
The transistor circuit of Figure 3 is then used to "amplify voltage." The input voltage, V_{in}, sets the base current and the collector current that flows through R_C is equal to I_B multiplied by β. The increase in voltage or current in a transistor amplifier is known as the circuit GAIN. Gain or amplification is represented as the letter "A." Thus:

current gain is A_i
voltage gain is A_v, and
power gain is A_p

Both current and voltage gain are demonstrated in Experiment No. 2, that follows.

OPERATING REGIONS

It has been explained that as the base current of a transistor increases, the collector current increases. Consider the circuit (a) and the plot of base current versus collector current (b) in Figure 4.



(a) BASIC CE AMPLIFIER

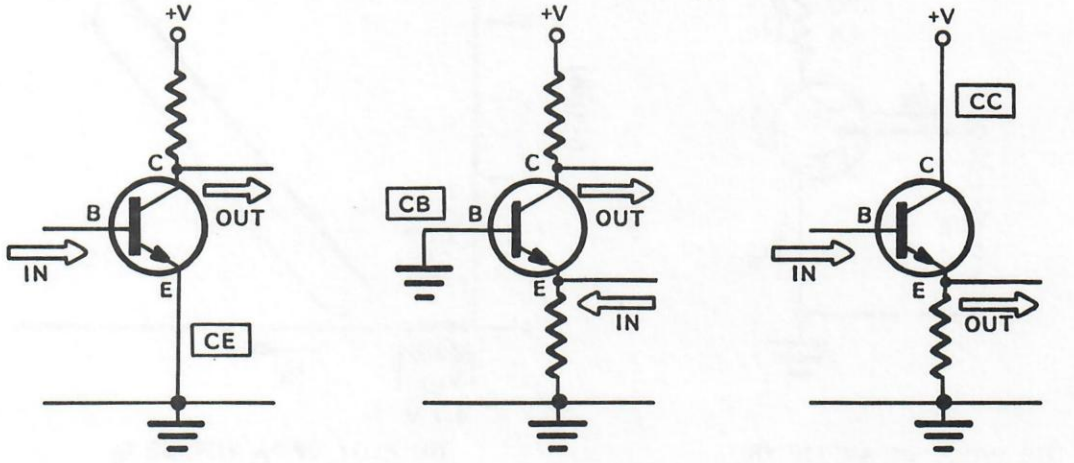
(b) PLOT OF I_C VERSUS I_B

Figure 4 - Transistor operating regions.

When the base-emitter voltage, V_{BE}, is 0, then I_B is 0. We know that I_C equals βI_B and if I_B is 0 then I_C must also be zero. As V_{BE} is increased there is still no base current until this voltage exceeds 0.7 volts, the barrier potential for Si, to enable base current to flow. When the collector current is not flowing because there is no base current, the condition is known as CUT-OFF. When the base current is increased, I_C increases at a rate equal to βI_B. This is shown as the ACTIVE or LINEAR area in Figure 4(b). As I_B and I_C continue to increase, a maximum collector current is reached. This value is governed by Ohm's Law where I_C is limited by $+V_{CC}$ (9 volts) and the value of R_C. Given an R_C of 1K, the maximum value of I_C is V_{CC}/R_C or 9/1K = 9 mA. As shown in the plot, further increases in I_B result in no further increases in I_C. This maximum current condition is called SATURATION.

CIRCUIT CONFIGURATIONS

The transistor INPUT is the small emitter to base current while the transistor OUTPUT is the large emitter to collector current. The small emitter to base current is controlled by the input voltage at the emitter or base. We can monitor the large output current at either the emitter or collector. This results in three possible arrangements or transistor "configurations" as shown in Figure 5.



(a) COMMON EMITTER (b) COMMON BASE (c) COMMON COLLECTOR

Figure 5 - Three transistor configurations, CE, CB and CC.

The circuit discussed earlier in Figure 4 is the common emitter (CE) configuration. The CE circuit is the most frequently used and will be the first covered in these experiments.

CURRENT GAIN, ALPHA (α)

In the common base (CB) configuration shown in Figure 5(b), the input is I_E in the emitter, and the output is I_C in the collector. In the common base configuration, the current gain or ratio is defined as ALPHA (α) and is given by:

ALPHA $$\alpha_{dc} = \frac{I_C}{I_E} \qquad (2)$$

Because I_E is slightly greater than I_C (recall that $I_E = I_C + I_B$), alpha is equal to slightly less than 1, typically 0.95 and greater. Given a transistor circuit where I_B is 0.05 mA and I_C is 5 mA, alpha is:

$$\alpha_{dc} = \frac{I_C}{I_E} = \frac{I_C}{I_C + I_B} = \frac{5}{5.05}$$

$$\alpha_{dc} = 0.99$$

When the transistor's beta value is known, the value of alpha can be determined from:

$$\alpha = \frac{\beta - 1}{\beta} \qquad (3)$$

Given a beta of 100, the same transistor used in a CB configuration will provide a current gain, alpha, of:

$$\alpha = \frac{\beta - 1}{\beta} = \frac{(100-1)}{100}$$

$$\alpha = 0.99$$

The exact value of alpha is not important and it is normally approximated as 1.

CURRENT GAIN, GAMMA (γ)

The current gain, beta (β), was covered above as the parameter of most interest in the common emitter circuit where the input is I_B and the output is I_C. In the common collector (CC) circuit of Figure 5(c) the input is to the base but the output is at the emitter. This (CC) current ratio is defined as GAMMA (γ) and is given by:

GAMMA $$\gamma_{dc} = \frac{I_E}{I_B}$$

It can be shown that gamma is equal to:

$$\gamma = \beta + 1$$

Because beta is high, gamma can be approximated as equal to beta. As a result gamma is almost never used and so rarely even included in text or reference material.

EXPERIMENT OVERVIEW

Experiment No. 2, which follows this lesson, consists of three parts. In the first part you will vary the base current and observe the three operating regions, cut-off, active and saturation. You will then measure the circuit current gain and then the voltage gain for the CE configuration.

KEY TERMS

1. ACTIVE REGION

   The area of operation of a transistor amplifier where variations in collector current are directly proportional to variations in base current.

2. AMPLIFIER

   A device or circuit that obtains its power from a source other than the input signal and provides a duplicate of the input at its output terminals. The output signal has its voltage level, current level and/or power level increased. The amount of signal increase, called the gain and indicated as A, is given by output/input.

3. COMMON BASE CONFIGURATION

   A circuit in which the transistor is connected so that the base element is common to both the input and output circuits. The current gain for this circuit is defined as alpha (α) and equal to I_C/I_E.

4. COMMON COLLECTOR CONFIGURATION

   A circuit in which the transistor is connected so that the collector element is common to both the input and output circuits. The current gain for this circuit is defined as gamma (γ) but approximated as β.

5. COMMON EMITTER CONFIGURATION

   A circuit in which the transistor is connected so that the emitter element is common to both the input and output circuits. The current gain for this circuit is defined as beta (β) and equal to I_C/I_B.

6. CURRENT GAIN (A_i)

   A measure of output current versus input current for any circuit, expressed as:

$$A_i = \frac{I_{out}}{I_{in}}$$

7. CUT-OFF REGION

The region of transistor operation where the base current is zero resulting in no collector current.

8. dc ALPHA

The ratio of collector current to emitter current in a transistor wired in a CB configuration. It is less than 1 and typically greater than 0.95 and is expressed as:

$$\alpha_{dc} = \frac{I_C}{I_E}$$

9. dc BETA

The ratio of collector current to base current in a transistor wired in a CE configuration. It is normally between 50 and 200 or more and is expressed as:

$$\beta_{dc} = \frac{I_C}{I_B}$$

10. dc GAMMA

The ratio of emitter current to base current in a transistor wired in a CC configuration. It is a rarely used rating as it is equal to $\beta + 1$ and so is simply estimated as equal to beta.

11. FORWARD BIAS

A voltage applied to a PN junction in such a polarity as to cancel the barrier potential and cause a current flow.

12. LINEAR REGION

The same as the "Active Region." See No. 1 above.

13. REVERSE BIAS

A voltage applied to a PN junction in such a polarity as to reinforce the barrier potential and block current flow.

14. SATURATION REGION

The region of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B will not increase I_C. Also V_{CE} is low, frequently no more than several tenths of a volt.

15. VOLTAGE GAIN

A measure of how much an amplifier or transistor circuit can increase the input signal voltage level. It is expressed as:

$$A_v = \frac{\Delta V_{out}}{\Delta V_{in}}$$

ASSIGNMENT

Answer the following questions.

1. Draw the block symbol for a transistor with an NPN sequence and label the terminals.

2. Draw the circuit symbol used to represent a transistor with an NPN sequence and label the terminals.

3. a) Draw the block symbol of the PNP transistor.
   b) Label the terminals.
   c) Connect two batteries to the transistor junctions to correctly bias the transistor.

4. a) Write the equation for dc alpha in terms of transistor element currents.
   b) Write the equation for alpha in terms of beta.

5. Write the equation for dc beta in terms of transistor currents.

6. Write the equation for the current gain of a transistor wired in a CC configuration, in terms of:

   a) transistor element currents.

   b) beta (β).

Transistor Action 2

OBJECTIVES

When you finish this experiment you will be able to:

1. Properly apply bias voltages to a bipolar junction transistor by forward biasing the base-emitter junction and reverse biasing the base-collector junction.

2. Vary the bias voltages to operate the transistor in the three regions; cut-off; saturation and linear.

3. Measure the transistor current gains, Alpha and Beta.

4. Measure the voltage gain of a transistor CE circuit.

REFERENCES

CES Lesson J1-2, Transistor Voltages

ADDITIONAL EQUIPMENT REQUIRED

Digital Multimeter (Optional)

BACKGROUND

1. The transistor is operated properly with the base-emitter junction forward biased and the base-collector junction reverse biased.

2. The transistor circuit can operate in three modes or "REGIONS"; cut-off, saturation, and linear. The linear region operation is normal for amplifiers.

3. The Common Emitter current gain is denoted as "Beta."

4. This Experiment No. 2 is divided into three parts:

   2.1 Transistor Operating Regions
   2.2 Current Gain Ratios (Alpha and Beta)
   2.3 Voltage Gain of a Transistor Circuit

PROCEDURE

2.1 TRANSISTOR OPERATING REGIONS

In the first part of the experiment, you will vary the emitter to base bias current (the input) to operate the transistor in one of the three regions; cut-off, linear or saturation. The voltage applied to the base-emitter circuit is called an input, and is abbreviated V_{in}. The voltage taken from the collector is called the output and is abbreviated V_{out}. A graph of the output voltage versus input voltage is plotted to observe the three operating regions.

1. Wire the circuit shown in Figure 1.

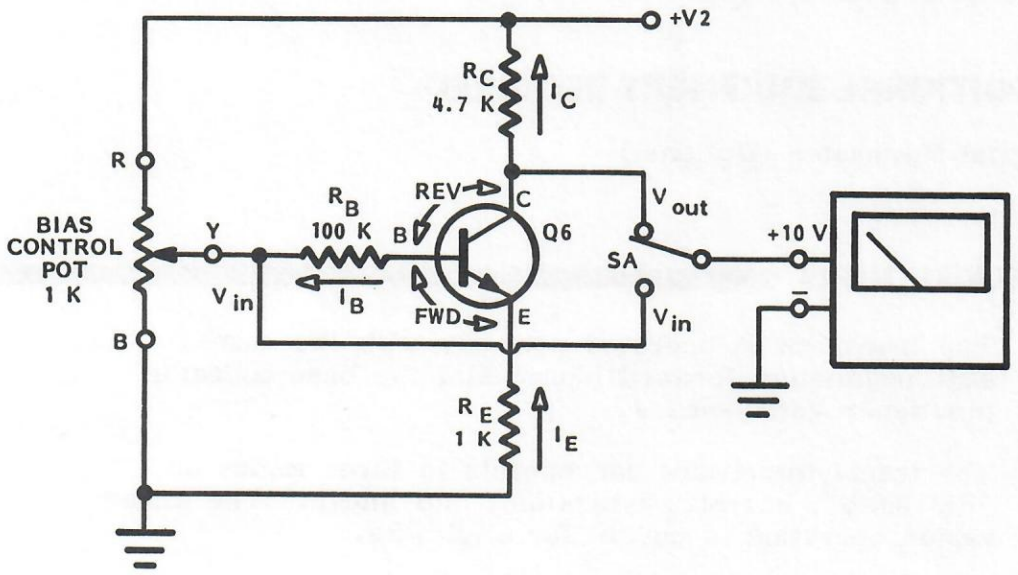


Figure 1 - Transistor operation EXPERIMENT.

In this circuit, the input base current is controlled by V_{in}, the setting of the 1K pot. The input bias current (emitter to base) is changed by varying V_{in}, the input voltage, measured from the wiper arm of the potentiometer to ground. The output, V_{out}, is measured from the collector to ground.

2. Although a transistor is a current operated device, you will first measure the circuit input voltage and output voltage to observe the operating modes.

Set switch SA DOWN to measure the input voltage, V_{in}, and vary the 1K pot for V_{in} = 0 volts. Move switch SA UP to measure V_{out}. Record the output voltage reading in Table 1.

Repeat this procedure of setting V_{in} for each input voltage (switch SA DOWN) listed in Table 1 and record each of the output voltages, V_{out}, (switch SA UP) in the same Table.

V_{in}	0	0.5	1	2	2.5	3	4	5	6	7	8	9
V_{out}												

Table 1 - Test data for V_{out} versus V_{in} for the transistor circuit of Figure 1.

3. Plot the results listed in Table 1 on the graph of Figure 2.

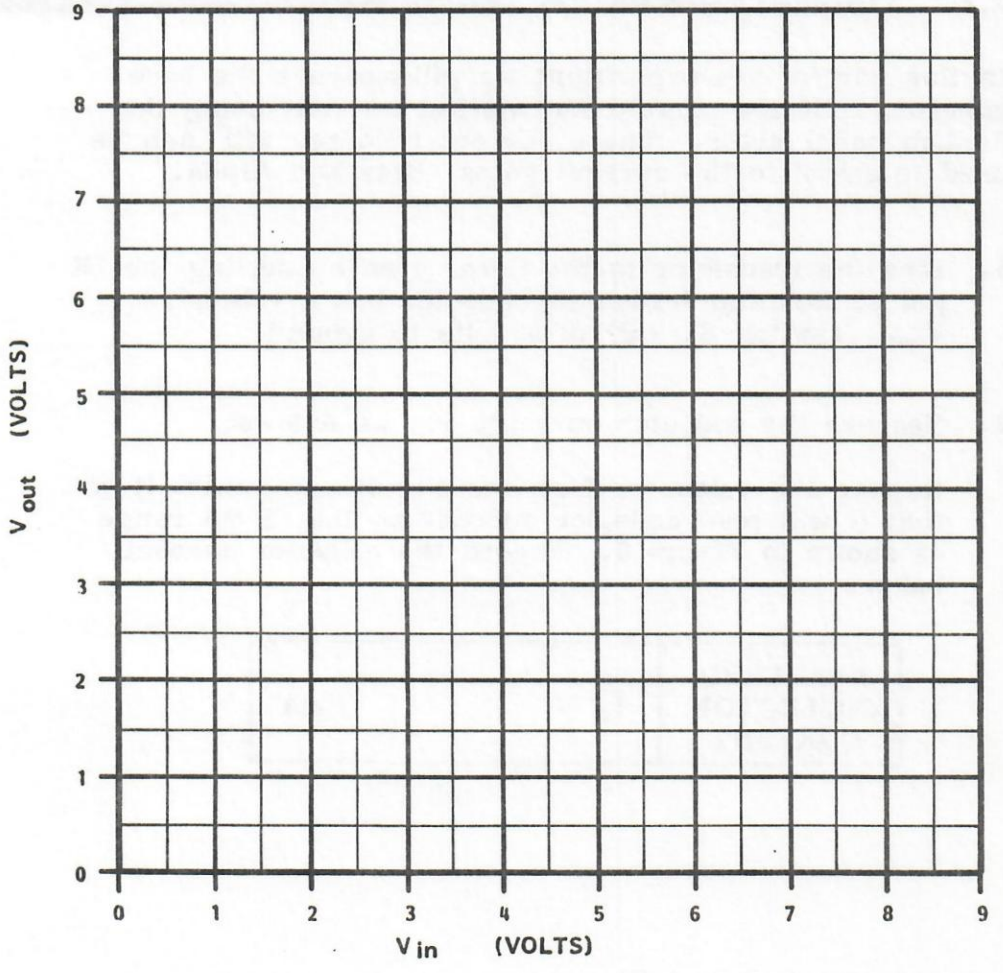


Figure 2 - Plot of V_{out} versus V_{in} for the transistor circuit of Figure 1.

4. Mark off the three "operating regions," cut-off, linear and saturation, on the curve plotted on the graph in Figure 2.

   In which operating region is the current maximum? _____

   _____

   When the collector current is maximum, the collector to ground voltage is _____ (minimum; maximum).

You can conclude from the above that varying V_{in} varies the base bias current. The variation in base current causes a variation in collector current which, in turn, causes a variation in collector output voltage. As I_B increases, I_C also increases, causing a reduction in V_{out}. By varying I_B, the transistor can be operated in one of three modes; cut-off, linear or saturation.

2.2 CURRENT GAIN RATIOS

In this part of the experiment we will measure the base current, collector current and emitter current using the Ed-Lab panel meter. These current readings will then be used to calculate the current gains, Beta and Alpha.

5. Bias the transistor in the linear area by setting the 1K pot so that the transistor collector has a voltage, V_{out}, (switch S_A UP) of 5 volts to ground.

6. Measure the collector current, I_C, as follows:

   Remove the voltmeter from the circuit and rewire it so that it will read collector current on the +5 mA range as shown in Figure 3. Record the collector current below.

MEASURED COLLECTOR CURRENT	I_C = mA

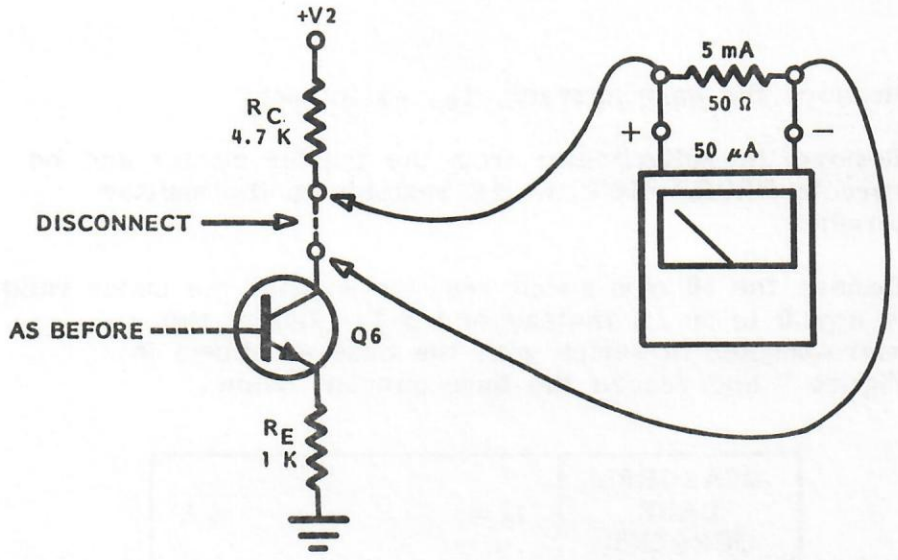


Figure 3 - Measuring I_C; EXPERIMENT.

7. Measure the emitter current, I_E, as follows:

   Remove the milliammeter from the collector circuit of Figure 3. BE SURE TO RECONNECT the 4.7K resistor to the Q6 collector terminal.

   "Break" the emitter circuit as shown in Figure 4. Measure and record the emitter current below.

MEASURED EMITTER CURRENT	I_E = mA

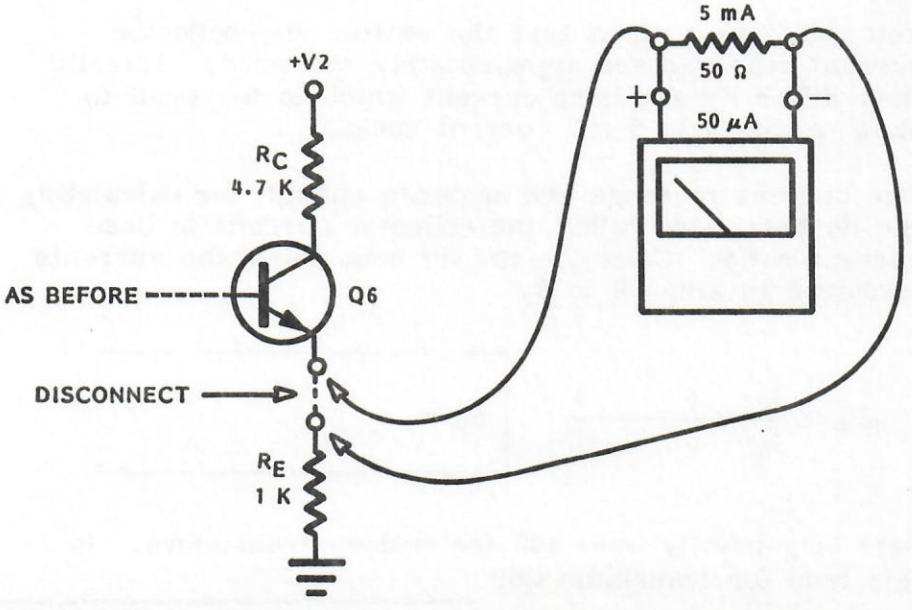


Figure 4 - Measuring I_E; EXPERIMENT.

8. Measure the base current, I_B, as follows:

Remove the milliammeter from the emitter circuit and be sure to RECONNECT the 1K resistor to the emitter terminal.

Remove the 50 ohm shunt resistor so that the meter range is now 0 to 50 μA instead of 5 mA. Insert the microammeter in series with the base as shown in Figure 5 and record the base current below.

MEASURED BASE CURRENT	I_B = μA

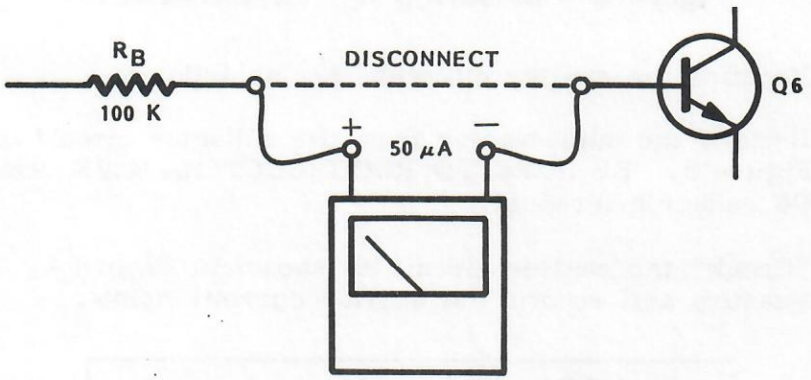


Figure 5 - Measuring I_B; EXPERIMENT.

9. BETA

You will have noticed that the emitter and collector current readings are approximately the same. Actually they differ by the base current which is too small to show on the 0 to 5 mA current scale.

The current readings are accurate enough for calculating the dc beta, also called the collector current to base current ratio. Calculate the dc beta using the currents measured in steps 6 to 8.

$$\beta_{dc} = \frac{I_C}{I_B} = \frac{(\quad)}{(\quad)} \qquad \beta_{dc} = \qquad (1)$$

Beta is generally over 100 for modern transistors. Is this true for transistor Q6? _____

10. ALPHA

The dc alpha, also called the collector to emitter current ratio, is defined as:

$$\alpha_{dc} = \frac{I_C}{I_E} \qquad (2)$$

As observed earlier, I_E and I_C are so close in value that the milliammeter could not show the small difference of approximately 4 μA. Even if you used a digital or analog voltmeter to measure the voltages across R_C and R_E and calculated the currents, you could not use the above equation because the tolerance of the resistors, and thus the error in the calculated currents, is greater than the difference in current between I_C and I_E. Even if you used separate digital meters reading current in the collector and emitter, the error of the meter readings could be larger than the current difference. Thus, the above equation should not be used directly to accurately calculate alpha. Because you know that I_E equals the sum of I_B plus I_C, the equation for alpha may be rewitten as:

$$\alpha_{dc} = \frac{I_C}{I_E} = \frac{I_E - I_B}{I_E} \qquad (3)$$

11. Calculate the dc alpha using equation (3).

$$\alpha_{dc} = \frac{I_C}{I_E} = \frac{I_E - I_B}{I_E} = \frac{(\quad)(\quad)}{(\quad)}$$

MEASURED ALPHA	α_{dc} =

Alpha values are normally slightly less than 1. Is the value of alpha as expected? _____

Because alpha is so close in value to 1, it is usually approximated as 1 when it is used for design calculations.

You can conclude from the above that the current gain of a transistor circuit, β, is the ratio of the collector current to the base current and is expressed as $\beta = I_C/I_B$. The alpha current gain is computed from $\alpha = I_C/I_E$. Because the

difference between I_E and I_C is difficult to measure, alpha is usually calculated from $\alpha = (I_E - I_B)/I_E$. Beta is high and over 100 and Alpha is close to but less than 1.

2.3 VOLTAGE GAIN OF A TRANSISTOR CIRCUIT

In this part of the experiment we will determine the voltage gain of the circuit. An input voltage (V_{in}) was fed to the base in Figure 1 and an output voltage (V_{out}) was measured at the collector. The voltage gain, A_v, is defined as the ratio of the change or difference, called delta (Δ), in output voltage to the change (Δ) in input voltage and is written as:

VOLTAGE GAIN	$A_v = \frac{\Delta V_{out}}{\Delta V_{in}}$

(4)

We will now determine the voltage gain from the curve plotted in Figure 2. This is a measured voltage gain.

12. Working in the linear region in Figure 2, mark off a delta V_{out} from 4 to 6 volts ($\Delta V_{out} = 2$ volts). Observe the corresponding change in V_{in} required to accomplish an output voltage change from 4 to 6 volts and enter the values below.

FOR A ΔV_{out} OF 2 VOLTS	$\Delta V_{in} = (\quad) - (\quad)$

13. Calculate A_v from:

$$A_v = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{(\quad) - (\quad)}{(\quad) - (\quad)} = \frac{(\quad)}{(\quad)}$$

MEASURED GAIN	$A_v =$

The voltage gain expected from this circuit is approximately 3. Is the voltage gain, A_v, calculated above, for the circuit of Figure 1 close to this value? _____

There are various other transistor circuits, to be studied in the following experiments, with voltage gains that can be much higher, up to 200 or more.

You can conclude from the above that some transistor amplifier circuits produce a voltage gain. This means that the output voltage is greater than the input voltage by a factor of A_v. This may be expressed as:

$$A_v = \frac{\Delta V_{out}}{\Delta V_{in}}$$

CONCLUSIONS

We have learned from this experiment that:

1. In order to amplify, the base-emitter junction of a transistor must be forward biased and the base-collector junction must be reverse biased.

2. The required bias voltages may be obtained from two separate power sources or a single power source and voltage divider.

3. The transistor amplifier circuit can operate in one of three regions; cut-off, saturation or the linear region.

4. The emitter, collector and base currents in a transistor are related by:

$$I_B = I_E - I_C \qquad I_E = I_B + I_C \qquad I_C = I_E - I_B$$

5. The dc alpha of a transistor is given by:

$$\alpha_{dc} = \frac{I_C}{I_E}$$

6. The alpha of a transistor is always less than one.

7. The dc beta of a transistor is given by:

$$\beta_{dc} = \frac{I_C}{I_B}$$

8. The value of beta generally runs 50 or more.

9. The collector current varies directly as the base current varies.

10. The collector current is given by:

$$I_C = \beta I_B$$

11. As V_{in} increases, I_B also increases.

12. As I_B increases, I_C increases.

13. As I_C increases, V_{RC} increases.

14. As V_{RC} increases V_C, the output voltage, decreases.

15. As V_{in} increases, V_{out} decreases.

16. The value of I_E and I_C are so close that a milliammeter most often will not show a difference in readings.

17. Voltage gain can be determined by measuring V_{in} and V_{out} and using the equation $A_v = V_{out} / V_{in}$.

KEY TERMS

1. ACTIVE REGION

   The area of operation of a transistor amplifier where variations in collector current are directly proportional to variations in base current.

2. CURRENT GAIN

   A measure of output current versus input current, expressed as:

$$A_i = \frac{I_{out}}{I_{in}}$$

3. CUT-OFF REGION

   The region of transistor operation where the base current is zero resulting in no collector current and thus maximum collector voltage.

4. dc ALPHA

   The ratio of collector current to emitter current. It is normally greater than 0.95 and less than one and is expressed as:

$$\alpha_{dc} = \frac{I_C}{I_E}$$

5. dc BETA

   The ratio of collector current to base current. It is normally between 90 and 250 or more and is expressed as:

$$\beta_{dc} = \frac{I_C}{I_B}$$

6. FORWARD BIAS

   A voltage applied to a PN junction in such a polarity as to cancel the barrier potential and cause a current flow.

7. LINEAR REGION

The same as the "Active Region." See No. 1 above.

8. REVERSE BIAS

A voltage applied to a PN junction in such a polarity as to reinforce the barrier potential and block current flow.

9. SATURATION REGION

The region of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also V_{CE} is low, frequently no more than several tenths of a volt.

10. VOLTAGE GAIN

A measure of how much an amplifier stage can increase the input signal voltage level. It is expressed as:

$$A_v = \frac{\Delta V_{out}}{\Delta V_{in}}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. In order for a transistor to amplify it is necessary to _____ bias the base-emitter junction and also _____ bias the base-collector junction.

   a. reverse; reverse
   b. forward; reverse
   c. forward; forward
   d. reverse; forward

2. A transistor amplifier circuit normally operates in the:

   a. cut-off region.
   b. saturation region.
   c. linear region.
   d. none of the above.

3. The current gain, Beta dc, is equal to:

   a. I_B/I_C.
   b. I_C/I_E.
   c. I_E/I_B.
   d. I_C/I_B.

4. The current gain, Alpha dc, is equal to:

   a. I_B/I_C.
   b. I_C/I_E.
   c. I_E/I_B.
   d. I_C/I_B.

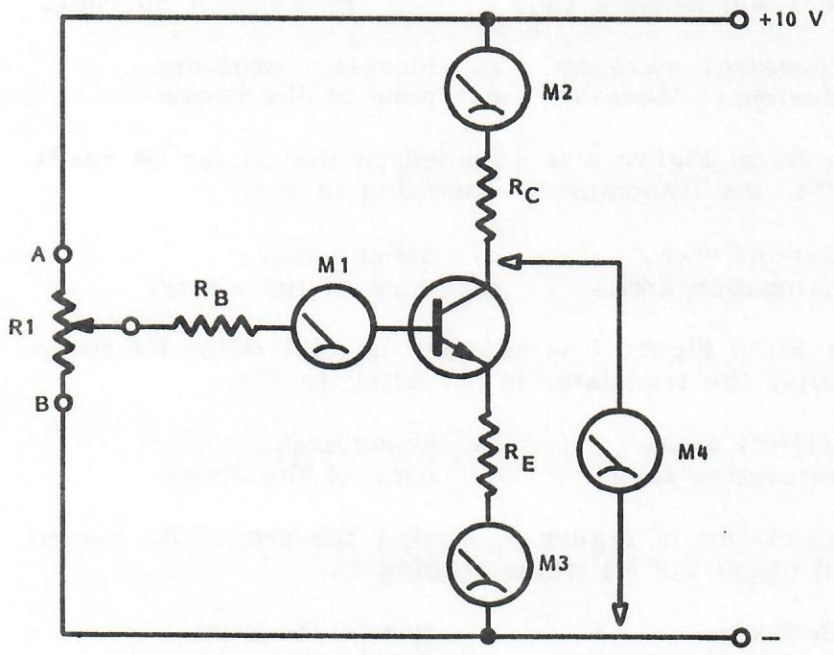


Figure 6 above refers to questions 5 to 15.

5. In the circuit of Figure 6, the reading on meter M2, subtracted from the reading on meter M3 will:

   a. give the collector current.
   b. give the emitter current.
   c. be equal to $I_C + I_E$.
   d. equal I_B but not be accurate.

6. In the circuit of Figure 6, moving the arm of R1 toward end A will cause the reading on M1 to _____ and the reading on M2 to _____ .

   a. increase; increase.
   b. increase; decrease.
   c. decrease; decrease.
   d. decrease; increase.

7. If the meters, M2 and M3, in Figure 6, were accurate enough, the M3 - M2 readings would be equal to:

   a. I_C.
   b. I_B.
   c. I_E.
   d. I_{source}.

8. In the circuit of Figure 6, varying R1 can place the transistor in:

   a. cut-off.
   b. saturation.
   c. the linear region.
   d. any of the above.

9. In the circuit of Figure 6, a (an) _____ in base current will cause a (an)_____ in collector current.

   a. increase; increase
   b. decrease; increase
   c. increase; decrease
   d. none of the above

10. When R1 in Figure 6 is adjusted so that meter M4 reads 5 volts, the transistor is operating in the:

    a. cut-off area.
    b. saturation area.
    c. linear area.
    d. none of the above.

11. When R1 in Figure 6 is adjusted so that meter M4 reads 10 volts, the transistor is operating in the:

    a. cut-off area.
    b. saturation area.
    c. linear area.
    d. none of the above.

12. In the circuit of Figure 6, moving the arm of R1 toward A will cause the M4 meter reading to:

    a. increase.
    b. decrease.
    c. remain the same.
    d. decrease then increase.

13. In Figure 6, given a base current of 40 μA, an emitter current of 1.5 mA, the collector current will be _____ mA and alpha will be _____.

a. 1.46; 0.973
b. 1.54; 1.02
c. 1.46; 36.5
d. none of the above.

14. Given a base current of 15 μA, an emitter current of 2 mA, in Figure 6, the dc Beta is closest to:

a. 1.985
b. 0.992
c. 30
d. 132

15. For the circuit of Figure 6, a change of 0.5 volts at the arm of R1 causes a change of 3 volts on meter M4. This indicates a voltage gain of:

a. 0.5
b. 3
c. 6 volts
d. 6

Transistor Characteristic Curves

INFO SHEET 2

OBJECTIVES

When you finish this information sheet you will be able to:

1. Define what is meant by a Characteristic Curve.
2. Plot a load line for a series diode and resistor circuit and locate the operating point.
3. Draw a family of transistor collector characteristic curves.
4. Plot the load line on the collector characteristic curves given the values of R_C and V_{CC} and locate the operating or "quiescent" point (Q point).
5. Draw a transistor input base-emitter characteristic curve.
6. Determine the output ΔI_C and ΔV_{CE} on the collector curves, given I_B.
7. Use the collector characteristic curves to demonstrate the clipping effect caused by an improper operating point.

DISCUSSION

The CHARACTERISTIC CURVE of any electrical device is a graph or plot which describes the characteristics or circuit behavior of the device. This curve is useful when analyzing the operation of a circuit and for design purposes. For simple two-terminal passive devices, as studied earlier, the characteristic curve is a plot of the voltage across the device, V_D, versus the current, I_D, flowing through it as shown in Figures 1(a), (b), (c) and (d).

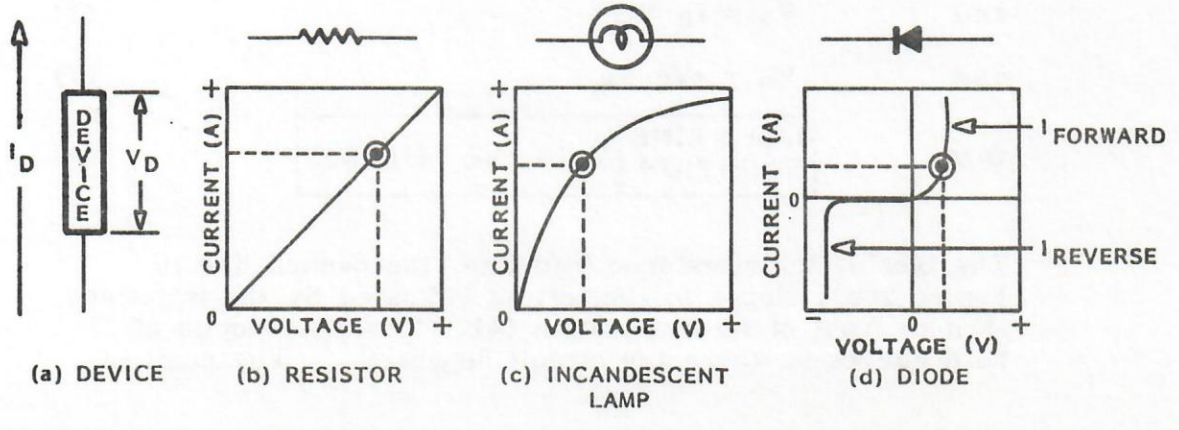
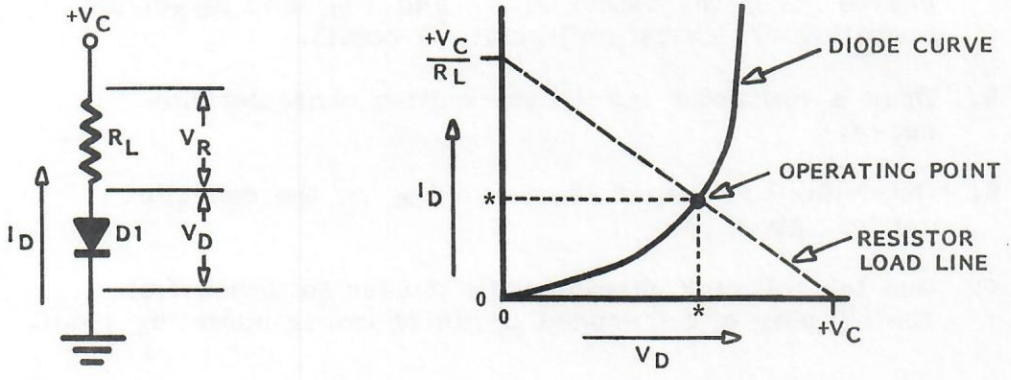


Figure 1 - E-I characteristic curves for various components.

At any given time, the devices in Figure 1 must be operating at some point on the curve and at only one point, typically as circled in Figures 1(b), (c) and (d).

LOAD LINE

If a component, such as the diode, is placed in series with a resistor, as shown in Figure 2(a), then the "resistor characteristic curve" can be plotted on the same graph with the "diode characteristic curve" as shown in Figure 2(b). The resistor is the "load" so its characteristic curve is called the LOAD LINE.



(a) DIODE CIRCUIT (b) DIODE AND RESISTOR CURVES

Figure 2 - Characteristic curve and load line.

The resistor load line in Figure 2(b) is a function of V_R versus the current, I_D. The point at which the resistor load line intersects the diode curve indicates the operating point, that is, the diode voltage drop and diode current as indicated by the asterisk on each axis. The equations to determine V_D, called the Load Line Equation, are:

If $$+V_C = V_R + V_D \quad (1)$$

and $$V_R = I_D R_L \quad (2)$$

and $$V_D = +V_C - V_R \quad (3)$$

then

LOAD LINE EQUATION	$V_D = +V_C - (I_D R_L)$

(4)

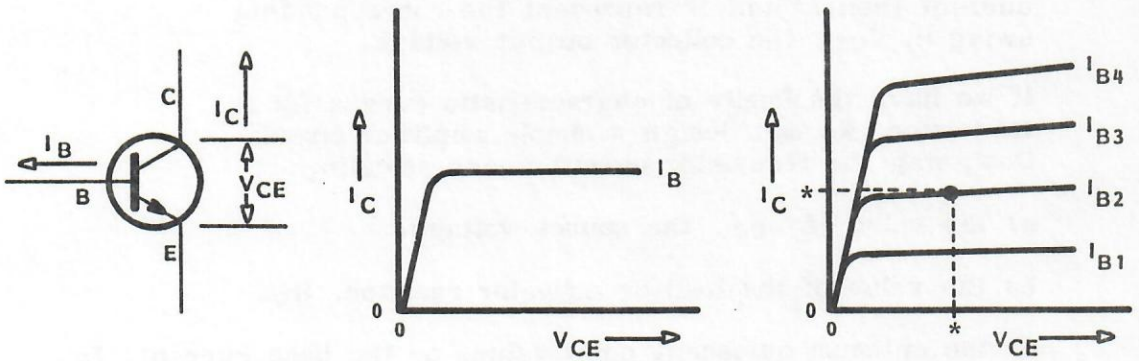
The plot of the resistance load line, the dashed line in Figure 2(b), slopes to the left as indicated by the negative sign in front of I_D in equation (4). The intersection of both curves is where the circuit "operates." The point of

intersection indicates the specific values of V_D and I_D at which the circuit operates and is, therefore, called the OPERATING POINT.

TRANSISTOR CURVES

A device such as a transistor has three connections; it is a "three terminal device." If the output is taken from the collector to emitter , V_{CE} , as shown in Figure 3(a), then it is the collector characteristic curve and is drawn plotting voltage (V_{CE}) and current (I_C) that flows from emitter to collector as shown in Figure 3(b).

Because the base current can be varied, and it affects the collector current, there is a curve for each different value of base current. This results in a SET or FAMILY of CHARACTERISTIC CURVES as shown in Figure 3(c). At any one instant of time, the circuit operates at one point on one curve, typically as shown in Figure 3(c).



(a) TRANSISTOR CURRENTS

(b) SINGLE CURVE; CONSTANT I_B

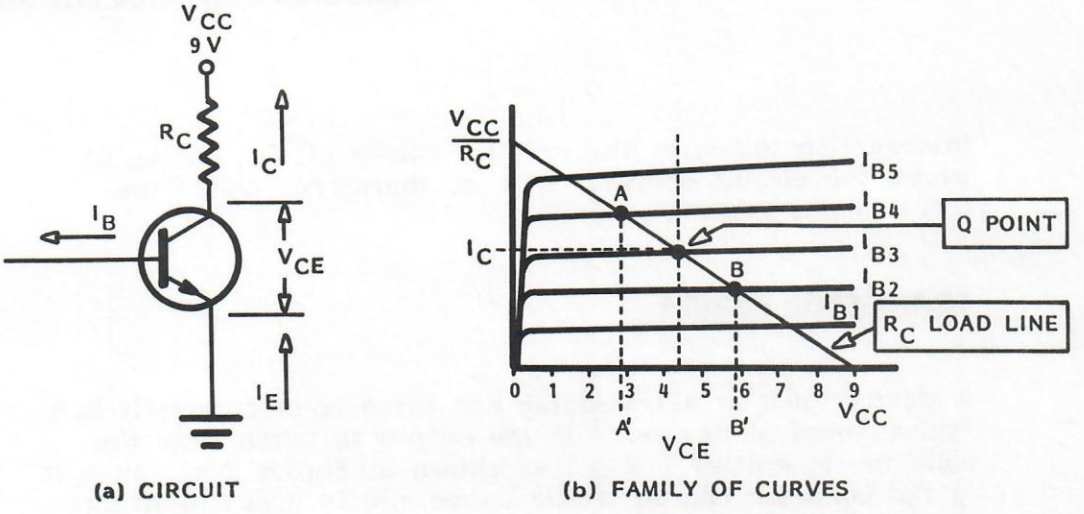
(c) FAMILY OF CURVES FOR DIFFERENT I_B

Figure 3 - Transistor characteristic curves.

TRANSISTOR LOAD LINE

When a resistor (R_C) is placed in the collector circuit of a transistor, as shown in Figure 4(a), a resistor load line is plotted as with the diode shown earlier in Figure 2. The load line for R_C is shown in Figure 4(b) and the circuit must always operate only at points along the load line.

4—TRANSISTOR CHARACTERISTIC CURVES



(a) CIRCUIT (b) FAMILY OF CURVES

Figure 4 - Load line plot and Q point.

The normal dc base bias current, (I_{B3}) without any input signal present, should be at the approximate V_{CE} midpoint. This "operating point" is also called the QUIESCENT POINT or Q POINT as shown in Figure 4(b). As the ac signal voltage and current at the base vary, (I_{B2} to I_{B4}) the operating point moves up and down the load line to the points marked A and B. If A to B represents the swing in input base current then A' and B' represent the corresponding swing in V_{CE}, the collector output voltage.

If we have the family of characteristic curves for a transistor, we can design a simple amplifier circuit. Designing the transistor circuit means selecting:

a) the value of V_{CC}, the source voltage.

b) the value of the load or collector resistor, R_C.

c) the optimum quiescent point value, or the base current, I_B.

We can also use the characteristic curves to determine beta at the selected operating point and to predict the amplifier current gain.

INPUT BASE-EMITTER CURVE

In order to use the collector characteristic curves, it is necessary to know the base current, I_B. In the transistor, the base-emitter junction is forward biased by a bias voltage source labelled V_B. This bias voltage and the input ac signal voltage are wired in series and connected across the base-emitter junction as shown in Figure 5(a).

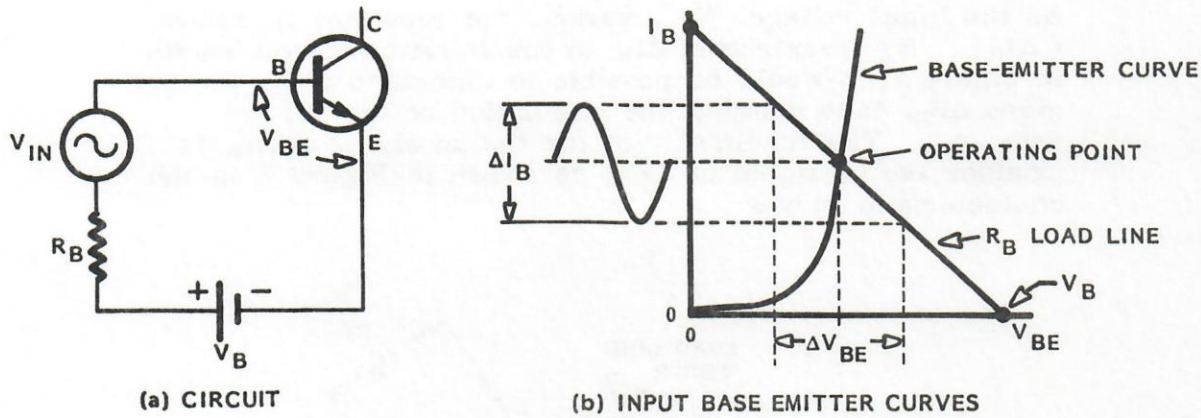


Figure 5 - Input circuit and base-emitter load line.

The base current, I_B, without an ac input signal (V_{in}) is determined by V_B and R_B. Figure 5(b) is the input Base-Emitter Characteristic Curve. The R_B load line can be plotted on the base-emitter curve and the intersection determines I_B as shown in Figure 5(b). When the ac input signal, V_{in}, is present, I_B varies on the base-emitter curve as shown in Figure 5(b). The varying base current, I_B, then relates to the collector curves and causes I_C to vary, with the I_C variation being identical in waveshape but greater by a factor of the current gain, beta.

VOLTAGE GAIN

A basic transistor voltage amplifier circuit is shown in Figure 6. The voltage gain for this circuit is defined by equation (6), also shown in Figure 6.

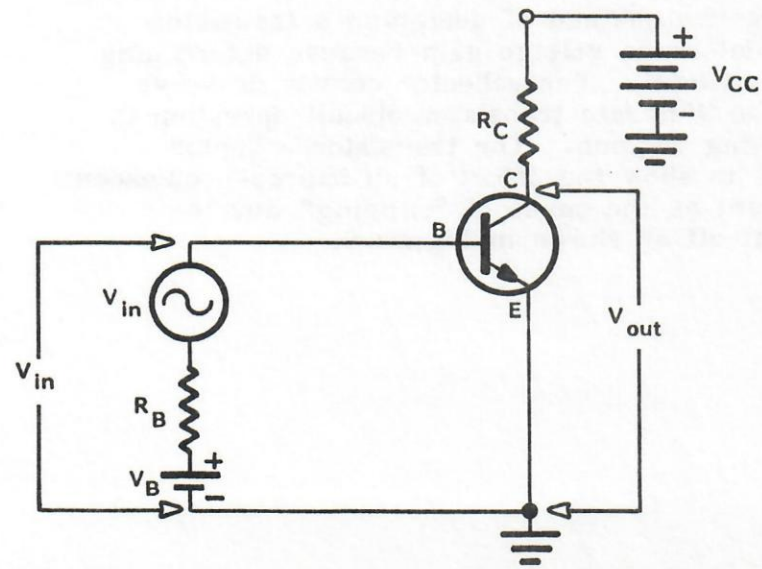


Figure 6 - Basic voltage amplifier and gain equation.

As the input voltage, V_{in}, varies, the resultant I_B varies (ΔI_B). By transferring ΔI_B to the collector curves shown in Figure 7, it would be possible to determine ΔV_{CE} for the given ΔI_B, thus allowing the calculation of the voltage gain, A_v. The resultant plot for the ac signal of ΔI_B to produce the ac signal of ΔV_{CE} is shown in Figure 7 on the characteristic curves.

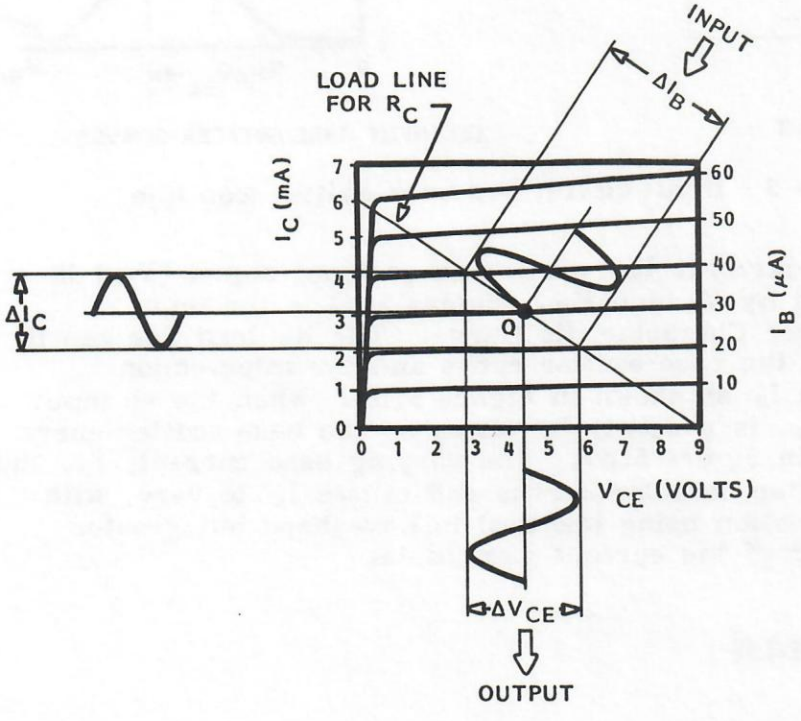
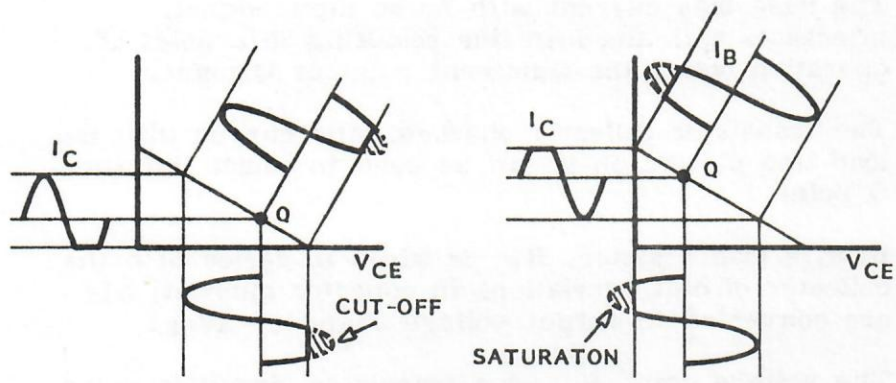


Figure 7 - Plot of I_B versus I_C and V_{CE}.

This process to calculate gain, however, is too complicated and is not a practical method of designing a transistor amplifier or to determine voltage gain because determining I_B from V_{in} is difficult. The collector curves do serve well, however, to illustrate transistor circuit operation in the three operating regions. The transistor collector curves are used to show the effect of an improper quiescent point base current as the cause of "clipping" due to saturation or cut-off as shown in Figure 8.



(a) CLIPPING AT TOP OF OUTPUT DUE TO CUT-OFF

(b) CLIPPING AT BOTTOM OF OUTPUT DUE TO SATURATION

Figure 8 - Clipping of output due to improper Q points.

The load line is used to show how the signal waveform will appear at the output of an amplifier. This is important in certain types of circuits to be studied later. A much easier method to determine gain is by use of "models" as described in the following information sheet.

CONCLUSIONS

We have learned from this information sheet that:

1. A characteristic curve of any device is a plot of voltage versus current.

2. A transistor base-emitter junction current flow varies with the applied voltage, V_{BE} or V_{IN}.

3. The transistor collector characteristic curve is a plot of I_C versus V_{CE} with I_B held constant.

4. A different collector characteristic curve is plotted for various values of I_B resulting in a "family" of curves for the transistor.

5. A load line may be drawn on the collector characteristic curves to permit plotting the output voltage "swing," ΔV_{CE}, for a given "swing" in ac input current, ΔI_B.

6. The intercept points for the load line are:

$$X \text{ Axis} = V_{CC}$$

$$Y \text{ Axis} = V_{CC}/R_C$$

The slope of the load line is determined by the value of R_C.

7. The base bias current with no ac input signal, intersects with the load line resulting in a point of operation called the Quiescent point or Q point.

8. The transistor collector characteristic curves with the load line plotted on it can be used to select the ideal Q point.

9. When a load resistor, R_C, is wired in series with the collector circuit, variations in collector current, ΔI_C, are converted to output voltage changes, ΔV_{CE}.

10. The voltage gain, A_v, of a transistor circuit is given by:

$$A_v = \frac{V_{out}}{V_{in}}$$

11. Improper selection of the Q point for a transistor circuit can cause clipping of the output signal voltage due operation in the saturation and cut-off regions.

KEY TERMS

1. CHARACTERISTIC CURVE

   A graphic plot that shows the relationship between voltage and current for a device.

2. CLIPPING

   In a transistor amplifier, when the input ac signal swings the collector current into the saturation or cut-off areas, the positive or negative peaks of the output signals are clipped off.

3. COLLECTOR CHARACTERISTIC CURVE (FAMILY)

   The graphic plot that shows how I_C varies with V_{CE} given a fixed value of I_B. The family of curves is a plot for various values of I_B.

4. LOAD LINE

   The Resistor Characteristic Curve (a straight line) plotted on a family of collector curves of a transistor that shows how current and voltage are related for the load resistor, R_C. It also shows how V_{CE} varies with changes in I_C caused by changes in I_B. The slope of the load line is determined by the value of R_C.

5. OPERATING POINT

   The steady state or dc value of I_C and the corresponding value of V_{CE} in a transistor circuit when no ac signal is present. Also called the quiescent or Q point.

6. Q POINT or QUIESCENT POINT

   See 5 above.

7. VOLTAGE GAIN

   Also called the voltage amplification, it is the ratio of the voltage output of a circuit or device to the voltage input and is expressed as:

$$A_v = \frac{V_{out}}{V_{in}}$$

ASSIGNMENT

Solve the following problems.

1. Calculate the X and Y intercept points of the load line for the circuit of Figure 9(a) and plot the load line on the graph in Figure 9(b).

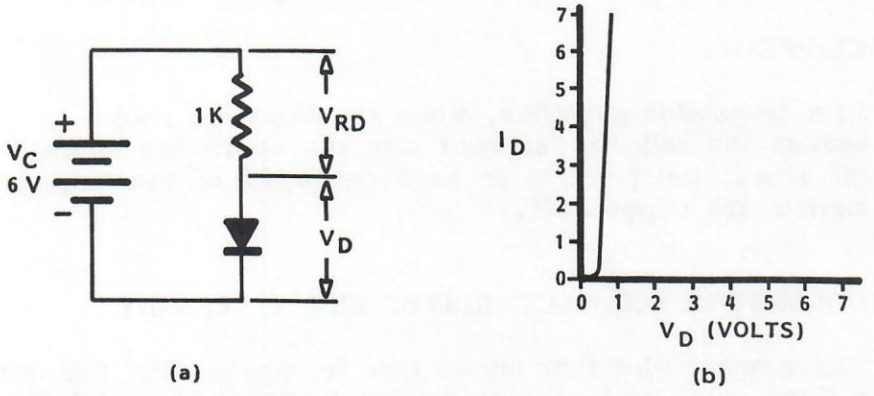


Figure 9 above refers to questions 1 to 3.

2. Approximate V_D from the data on the graph in Figure 9(b).

3. Calculate the X and Y intercepts points for the load line for the circuit of Figure 10(a) and plot the load line on the graph of Figure 10(b).

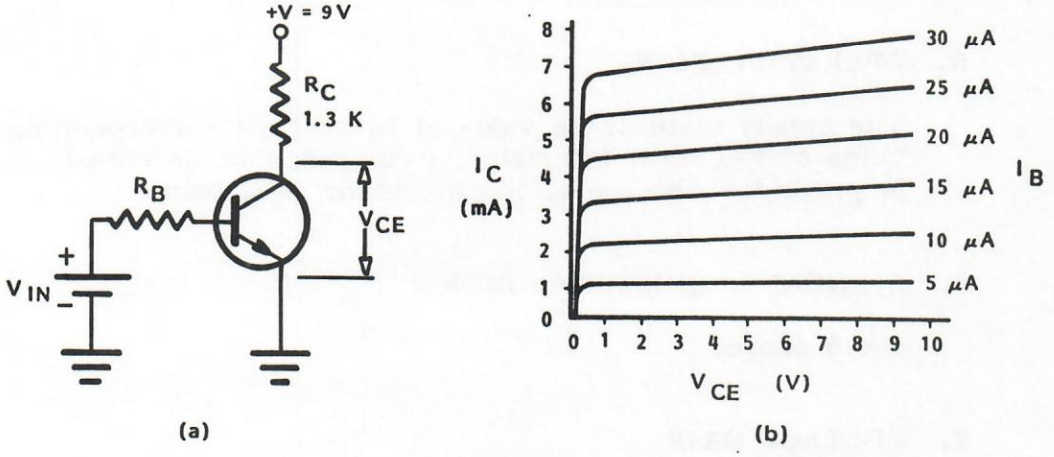


Figure 10 above refers to questions 3 to 7.

4. Determine the quiescent values for I_C and V_{CE} given a base current of 15 μA using the data in Figure 10.

5. Using the data in Figure 10, calculate the swing in I_C and V_{CE} for a 10 μA p-p input current.

Answer the following multiple choice questions.

6. If in the circuit of Figure 10(a), the operating point is shifted to 25 μA, the result will be:

   a. increased voltage gain.
   b. increased current gain.
   c. a drop of 50% in beta.
   d. clipping.

7. Given a transistor amplifier circuit such as shown in Figure 10(a) with an input signal voltage of 0.09 volts p-p, an output signal of 2.7 volts p-p and a current gain (beta) of 90, the voltage amplification is:

   a. 30.
   b. equal to β, 90.
   c. 2.7.
   d. 243.

Transistor Models

INFO SHEET 3

When you finish this information sheet you will be able to:

1. Draw the equivalent circuit or model of a transistor using the Ebers-Moll model and the "hybrid" h-parameter model.

2. Calculate the value of r'e, the base to emitter "dynamic resistance," given the value of the emitter current.

3. Calculate the input resistance at the base of a common emitter amplifier.

4. Draw three symbols used to indicate a current generator.

5. Calculate the voltage gain of a common emitter amplifier given the values of the collector load resistor, R_C, and emitter current, I_E.

6. Convert the h-parameters, frequently given, to the simpler Ebers-Moll equivalent circuit form for easier computations.

DISCUSSION

It was noted earlier that a transistor is an active device and must be correctly biased in order to operate properly. There are many possible bias or operating points and it was shown to be convenient to specify the transistor action graphically, using the family of collector characteristic curves.

When the transistor is used as an amplifier for small signals, using graphical analysis to determine amplifier gains is usually not practical. This is because it is a complicated and long procedure using both the input (base-emitter) curves and the output (collector-emitter) curves. The collector curves are useful when studying the effects of cut-off, saturation and the selection of a correct operating point. For "small signal" amplifiers (those amplifiers that have low input signal currents), it is more convenient to use a MODEL which is an EQUIVALENT CIRCUIT that shows the transistor as a part of an electrical network instead of using the characteristic curves. The model is for the transistor alone and it is assumed that it will be biased properly for operation in the LINEAR region with the base-emitter junction forward biased and the base-collector

junction reverse biased. Various transistor models may be used to determine circuit performance and two that are used most frequently are the:

a) Ebers-Moll model, or variations which use resistance (r) parameters, and the:

b) Hybrid model which uses hybrid (h) parameters.

Both models produce the same results and two variations of the Ebers-Moll model are shown in Figure 1. The hybrid model will be discussed shortly.

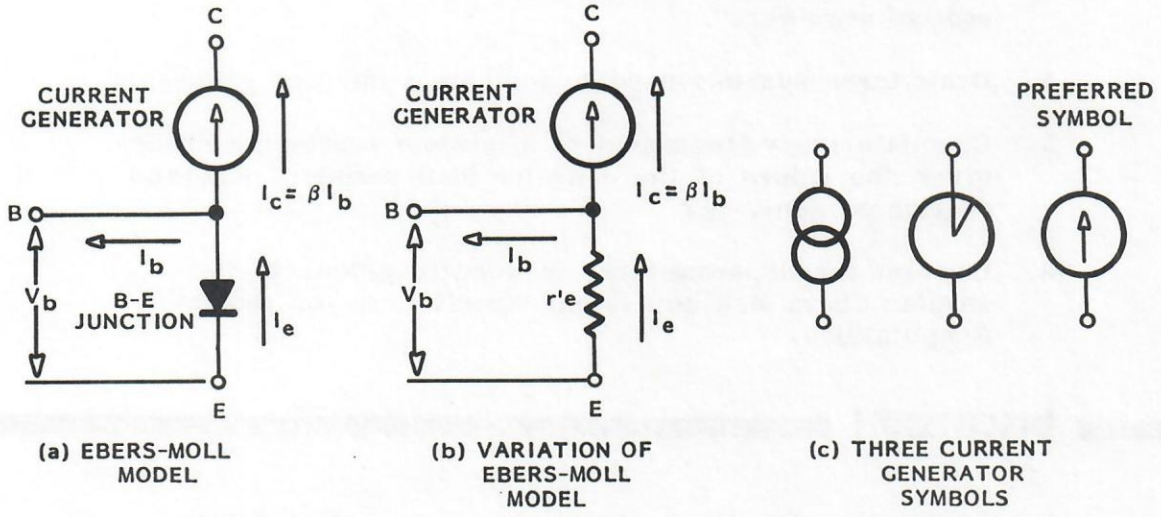


Figure 1 - Two variations of the Ebers-Moll model for the common emitter configuration. The circle with the arrow in the collector circuit is the symbol for a current generator.

The model shown in Figure 1(b) substitutes the eqivalent ac resistance of the base-emitter junction diode. Labelled r'e and pronounced R E PRIME, it is defined as an r-parameter.

EMITTER RESISTANCE (r'e)

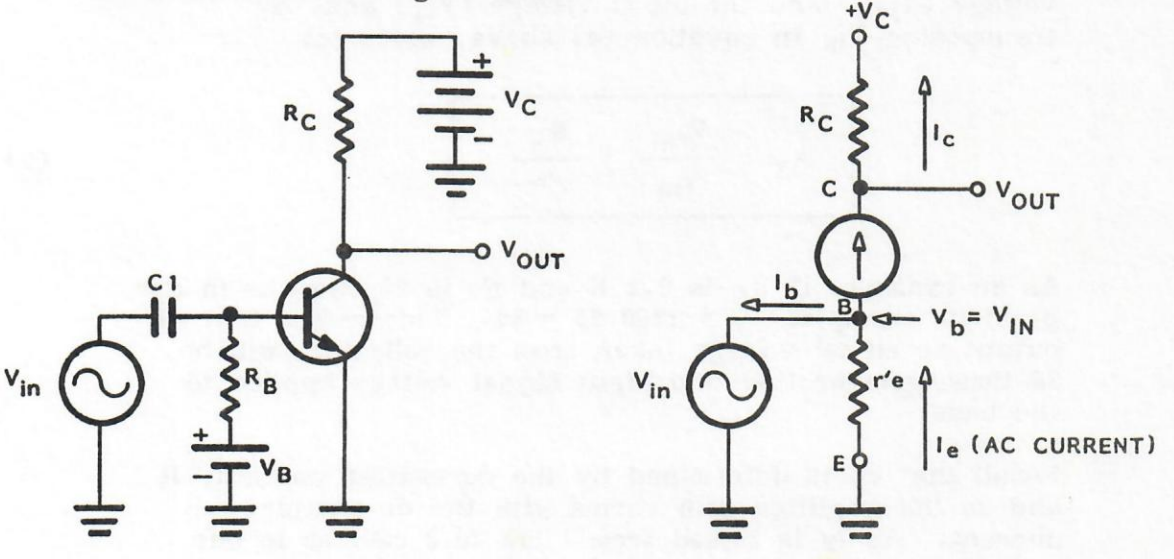
The base-emitter junction diode shown in Figure 1(a) offers a resistance, r'e, to the ac input signal current that flows through it. The JUNCTION RESISTANCE, r'e, is also known as the DYNAMIC JUNCTION RESISTANCE because it refers to the resistance seen at a particular operating point by the ac signal. The value of r'e may be determined in the same manner as the dynamic resistance of an ordinary diode as explained earlier in Unit H1, Diodes. The resistance of r'e is a function of the dc emitter current and is given by the approximation formula shown on the following page.

DYNAMIC JUNCTION RESISTANCE	$r'e \cong \frac{25}{I_E \text{ (in mA)}}$	(1)

Because the value of the emitter current in a transistor will vary from circuit to circuit, the value of r'e will also vary. As I_E is increased, the value of r'e will decrease. As an example, if I_E = 1 mA, then r'e = 25 ohms. If I_E is increased to 2 mA, then r'e = 12.5 ohms.

VOLTAGE AMPLIFICATION (A_v)

Voltage amplification, which is the ratio of output ac voltage to the input ac voltage and designated as A_v, is a major application for a transistor circuit. To determine the voltage gain produced by the transistor amplifier circuit shown in Figure 2(a), we first draw the equivalent model as shown in Figure 2(b).



(a) TRANSISTOR AMPLIFIER (b) EBERS-MOLL MODEL

Figure 2 - Transistor amplifier and its Ebers-Moll model.

The ac current flow in r'e is given by Ohm's Law and is:

$$I_e = \frac{V_{in}}{r'e} \qquad (2)$$

We use a capital letter E to denote dc current, I_E, as used to determine r'e and the small letter e to denote ac current, I_e, as in the above equation. Note that the base-emitter diode voltage drop of 0.7 volts (or 0.3 volts for germanium) is ignored because we are working with the "ac change" in voltage, not the dc level. The ac output voltage, V_{out}, is the voltage drop across the collector resistor, R_C, and is equal to:

$$V_{out} = I_c \, R_C \tag{3}$$

We also know that I_c and I_e are approximately equal and so we can substitute equation (2) for I_c to get:

$$V_{out} \cong \frac{V_{in}}{r'e} \, R_C \tag{4}$$

The voltage gain, A_v, is the ratio between the output voltage (V_{out}) and the input voltage (V_{in}) and, by transposing V_{in} in equation (4) above, we have:

$$A_v = \frac{V_{out}}{V_{in}} \cong \frac{R_C}{r'e} \tag{5}$$

As an example, if R_C is 2.2 K and r'e is 25 ohms as in our previous example, $A_v = 2200/25 = 88$. This means that the output ac signal voltage taken from the collector, will be 88 times greater than the input signal voltage applied to the base.

Recall that r'e is determined by the dc emitter current, I_E, and so the amplifier gain varies with the dc emitter current. As I_E is raised from 1 mA to 2 mA, as in our earlier example, r'e drops from 25 ohms to 12.5 ohms. The voltage gain, A_v, now increases because A_v now is equal to $2200/12.5 = 176$.

INPUT RESISTANCE

From the model for the common emitter configuration, as shown in Figure 2(b), it would appear that the input ac generator voltage source sees r'e as the resistance into which it must deliver the ac signal current. In reality,

however, the base signal current, I_b, is much lower than $V_{in}/r'e$ because at the junction, marked B (for base) in the model, there are three currents, I_b, I_e and I_c. Because I_c almost equals I_e and the base current, I_b, equals $I_e - I_c$, there is very little base current flow. The base input resistance is actually defined by Ohm's Law as:

$$R_{in} = \frac{V_{in}}{I_b} \tag{6}$$

Because I_b is very small, R_{in} is very large. We will now derive the equation for R_{in} in terms of available information because V_{in} and I_b are not known for the transistor of interest. The input signal base voltage, V_{in}, (which is also V_b) appears across r'e as shown in Figure 2(b), and determines the emitter signal current from:

$$I_e = \frac{V_b}{r'e} \tag{7a}$$

Because the collector current is approximately equal to the emitter current, equation (7a) may be rewritten as:

$$I_c \cong I_e = \frac{V_b}{r'e} \tag{7b}$$

It has also been shown, earlier, that the base current is related to collector current by the factor beta and is given by:

$$I_c = \beta I_b \tag{8a}$$

and, by transposing:

$$I_b = \frac{I_c}{\beta} \tag{8b}$$

Substituting equation (7b) for I_c in equation (8b), above, we now have:

$$I_b = \frac{V_b}{r'e\beta} \quad \text{or} \quad \frac{V_{in}}{r'e\beta} \tag{9}$$

The input resistance, R_{in}, of the transistor was defined earlier in equation (6) and is shown again.

$$R_{in} = \frac{V_{in}}{I_b} \tag{6}$$

Substituting equation (9) for I_b, transposing and cancelling, we have:

$$R_{in} = \frac{V_b}{\frac{V_b}{r'e\beta}}$$

which simplifies to:

DERIVED INPUT IMPEDANCE	$R_{in} = \beta r'e$	(10)

As an example, for the previous r'e of 12.5 ohms and a beta of 100, the input resistance at the base is:

$$R_{in} = \beta\, r'e = (100)\ 12.5 = 1250 \text{ ohms}$$

The concept of R_{in} can be used to determine the ac input base current, I_b, and is more conveniently done using equation (10) above from the model rather than the base-emitter characteristic curve. Because r'e varies with emitter current, R_{in} also varies with emitter current.

The use of this input resistance, R_{in}, as seen by the input generator, gives rise to a variation of the Ebers-Moll model as shown in Figure 3.

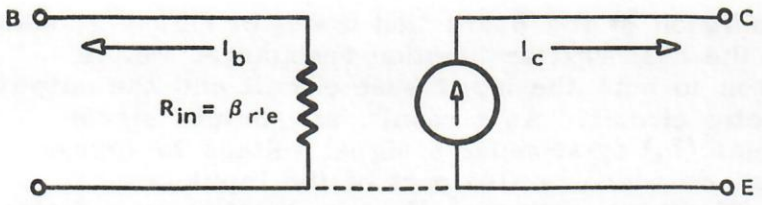


Figure 3 - A variation of the CE amplifier model.

The model of Figure 3 separates the input circuit from the output circuit. We know, however, from the description of Input Resistance on the previous page that the base current and emitter current both flow through r'e but this separation simplifies the analysis of some transistor circuits.

HYBRID MODEL (h-PARAMETERS)

The experiments in this and later manuals use the equations developed for the Ebers-Moll model with only occasional references to h-parameters. The information on the hybrid model and its parameters that follow are of interest because the data supplied by manufacturers' specification sheets use h-parameters.

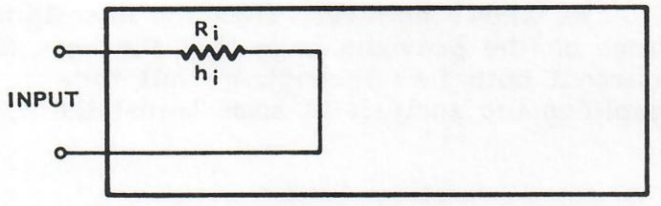
The HYBRID model is so named because a combination of test methods (open circuit tests and short circuit tests) are used to determine the transistor parameters. The parameters found for this model are called HYBRID PARAMETERS or simply h-parameters. The h-parameters are used to analyze the performance of a transistor amplifier circuit and consist of four measurements.

1. Input Resistance, h_i

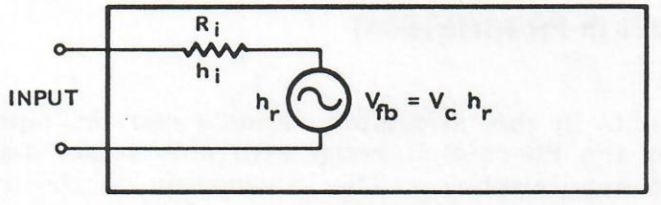
   The input resistance of the transistor amplifier was defined earlier as R_{in} in the Ebers-Moll model and given as V_{in} / I_{in}. In the hybrid model, the same input resistance is given the symbol, h_i and is represented in the model as shown in Figure 4(a). The unit of measurement for h_i is the ohm.

2. Reverse Voltage Transfer, h_r

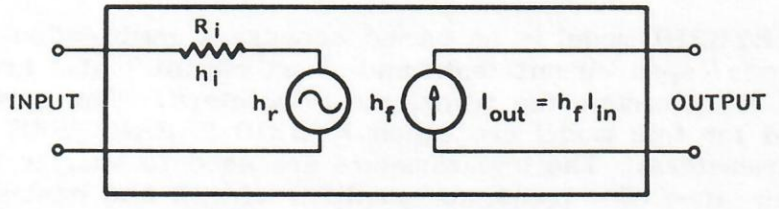
Examination of the Ebers-Moll model in Figure 1, shows that the base-emitter junction resistance, r'e, is common to both the input base circuit and the output collector circuit. As a result, any output signal current (I_c) must cause a signal voltage to appear across r'e which is also part of the input circuit. This "feedback voltage," V_{fb}, is denoted by a factor that is given the symbol h_r and has been added to the model in Figure 4(b). There is no unit for the h_r measurement as it is the ratio of V_{fb}/V_c with I_{in} held constant.



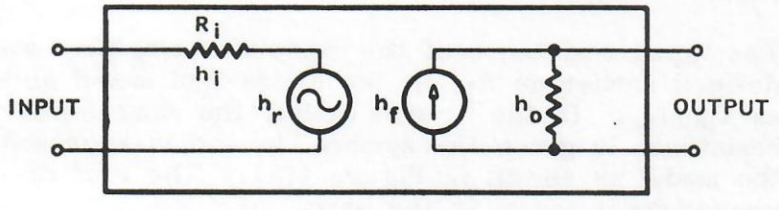
(a) HYBRID MODEL INPUT CIRCUIT



(b) INPUT WITH REVERSE VOLTAGE, h_r.



(c) OUTPUT CURRENT GENERATOR, h_f.



(d) COMPLETE MODEL WITH OUTPUT ADMITTANCE, h_o.

Figure 4 - Development of the hybrid model.

3. Forward Current Transfer Ratio, h_f

We know that an ac input signal current causes an ac output signal current in the transistor amplifier. This is defined as the FORWARD TRANSFER CURRENT RATIO or simply the FORWARD CURRENT GAIN and is given by the symbol h_f. The h_f equivalents in the Ebers-Moll model are alpha or beta. The current generator that represents h_f has been added to the hybrid model in Figure 4(c). There is no unit for the h_f measurement as it is the ratio of I_{out} / I_{in} with V_{CE} held constant.

4. Output Admittance, h_o

The output admittance of the transistor is defined as h_o which is the reciprocal of the output resistance. Thus, $R_{out} = 1/h_o$ and is the resistance seen by any load connected to the output circuit. The output resistance of the transistor is shown connected in parallel with the output current generator in Figure 4(d) to complete the hybrid model. The unit for h_o is the Siemen (S) which is equal to 1/R commonly referred to in earlier days as the "mho" (ohm spelled backwards) and given by the inverted omega ohms symbol (℧).

The hybrid model shown in Figure 4(d) is the same for all three configurations, CB, CE and CC. To be able to determine which configuration is represented by a hybrid model, a second subscript is added. The letter b is added to indicate CB, the letter e is added for CE and the letter c for CC. Thus, the forward current gains (h_f) are h_{fb}, h_{fe} and h_{fc} and are different for each configuration. Therefore h_{fe} (CE) is equal to beta, h_{fb} (CB) equals alpha, and h_{fc} (CC) equals gamma.

The above information is summarized in Table 1.

QUANTITY	CB	CE	CC	NUMERICAL	UNIT
INPUT RESISTANCE	h_{ib}	h_{ie}	h_{ic}	h_{11}	ohms
REVERSE VOLTAGE TRANSFER	h_{rb}	h_{re}	h_{rc}	h_{12}	ratio
FORWARD CURRENT GAIN	h_{fb}	h_{fe}	h_{fc}	h_{21}	ratio
OUTPUT ADMITTANCE	h_{ob}	h_{oe}	h_{oc}	h_{22}	siemens

TABLE 1 - Summary of h-parameters.

In Table 1, the column marked NUMERICAL lists a method of defining each parameter by numbers. An input measurement uses a 1 and an output measurement uses a 2. The Input Resistance, h_i, is measured from V_{in} / I_{in}, both input quantities; thus h_i may also be shown as h_{11}. The Forward Current Gain is equal to I_{out} / I_{in}, an output/input measurement which is shown as h_{21} and so on.

The h-parameters that are given by the transistor manufacturer in the Transistor Data Sheet have been determined experimentally. The h-parameters supplied may be for the CE circuit or the CB circuit. It is sometimes necessary to convert the h-parameters from CB to CE or CC. The approximations necessary to do so are given in Table 2.

FROM CB		FROM CE	
TO CE	TO CC	TO CB	TO CC
$h_{ie} = \frac{h_{ib}}{1 + h_{fb}}$	$h_{ic} = \frac{h_{ib}}{1 + h_{ib}}$	$h_{ib} = \frac{h_{ie}}{1 + h_{fc}}$	$h_{ic} = h_{ie}$
$h_{oe} = \frac{h_{ob}}{1 + h_{fb}}$	$h_{oc} = \frac{h_{ob}}{1 + h_{ob}}$	$h_{ob} = \frac{h_{oe}}{1 + h_{fe}}$	$h_{oc} = h_{oe}$
$h_{fe} = \frac{-h_{fb}}{1 + h_{fb}}$	$h_{fc} = \frac{-1}{1 + h_{fb}}$	$h_{fb} = \frac{-h_{fe}}{1 + h_{fe}}$	$h_{fc} = -(1 + h_{fe})$
$h_{re} = \frac{\Delta^{hb} - h_{rb}}{1 + h_{fb}}$	$h_{rc} \cong 1$	$h_{rb} = \frac{\Delta^{he} - h_{re}}{1 + h_{fe}}$	$h_{rc} \cong 1$

NOTE: $\Delta^h = (h_i\ h_o) - (h_r\ h_f)$

TABLE 2 - h-parameter conversion approximations.

The h-parameter values provided in a data sheet are correct only for the specified values of I_C and V_C (operating point) and one operating temperature (25°C, room temperature). Any variation in these quantities will change the values of the h-parameters. The data sheets often supply graphs that show how the h-parameters vary with I_C, V_C and temperature and provide correction factors that allow accurate performance calculations to be made.

USING h-PARAMETERS

Accurate transistor amplifier performance data, using h-parameters, requires the calculations shown in Table 3. The equations allow the calculation of precise values of R_{in}, R_{out}, A_i, A_v and A_p, the power gain of the stage.

QUANTITY	SYMBOL	EQUATION
INPUT RESISTANCE	R_{in}	$R_{in} = \dfrac{R_L\ \Delta^h + h_i}{h_o R_L + 1}$
OUTPUT RESISTANCE	R_{out}	$R_{in} = \dfrac{R_S + h_i}{R_S h_o + \Delta^h}$
CURRENT GAIN	A_i	$A_i = \dfrac{h_f}{h_f R_L + 1}$
VOLTAGE GAIN	A_v	$A_v = \dfrac{-h_f R_L}{R_L\ \Delta^h + h_i}$
POWER GAIN	A_p	$A_p = \dfrac{h_f{}^2\ R_L}{(1 + h_o R_L)(R_L\ \Delta^h + h_i)}$

NOTE: $\Delta^h = (h_i\ h_o) - (h_r\ h_f)$

TABLE 3 - Amplifier h-parameter performance equations.

The equations in Table 3 provide more accurate performance data than the equations developed from the Ebers-Moll model, but if the transistor is manufactured to within ± 20% of the provided specifications, there is very little need for more precise calculations. As a result, most often, the h-parameter data provided in transistor data sheets are converted to the simpler r-parameters given in the section on the Ebers-Moll model. A simple conversion process requires that you first convert any available h-parameter data so that it can be used for our simple model approximations, as shown in Table 4.

h-PARAMETER	EQUIVALENT r-PARAMETER	CONVERSION
h_{fe}	β	Equal
h_{fb}	α	Equal
h_{ie}	R_{in} (CE)	$\beta r'e$
h_{ib}	R_{in} (CB)	$r'e$

TABLE 4 - Summary of h-parameter and r-parameter equivalents.

When only h_{fb} (alpha) is known and it is beta that must be known, the conversion formula, given in an earlier information sheet, is:

$$\beta = \frac{\alpha}{(1 - \alpha)} \tag{11}$$

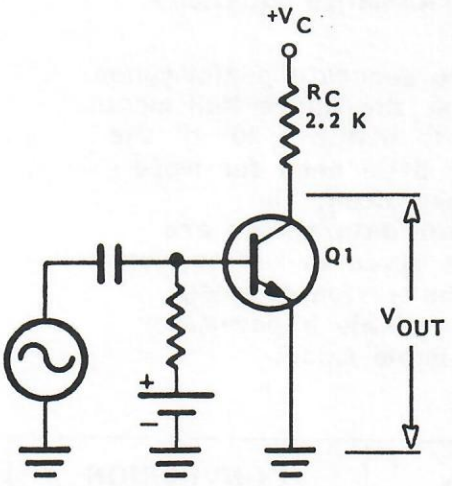
To convert from h_{fe} (beta) to alpha we use:

$$\alpha = \frac{\beta}{(1 + \beta)} \tag{12}$$

The remaining h-parameters, h_r and h_o, have no immediate application for our simple design approximations.

EXAMPLE

A transistor is to be used as an amplifier in the circuit shown in Figure 5(a) and the transistor data sheet provides the h-parameters for the transistor that are listed in Figure 5(b).



(a) CE AMPLIFIER

PARAMETERS	VALUE
h_{fb}	0.989
h_{ib}	30 Ω
h_{ob}	2 μS
h_{rb}	300×10^{-6}

(b) Q1 h-PARAMETERS

Figure 5 - Basic CE amplifier and transistor h-parameters.

We will now convert h_{fb} (α) to its equivalent value of beta using equation (11).

$$\beta = \frac{\alpha}{(1 - \alpha)} = \frac{0.989}{1 - 0.989} = 90$$

To find R_{in} for the CE configuration, given h_{ib}, we used equation (10) for the model because we know that h_{ib} equals r'e (Table 4). Thus:

$$R_{in} = \beta r'e = 90\ (30) = 2700\Omega$$

From this data, we can now determine the gains for current, voltage and power (A_i, A_v and A_p) without having to use the more complex equations listed earlier in Table 3 for the h-parameters, but rather, using the r-parameter model equivalents. For the circuit of Figure 5(a) we have:

CURRENT GAIN $\quad A_i \cong \beta = 90$

VOLTAGE GAIN $\quad A_v = \frac{R_C}{r'e} = \frac{R_C}{h_{ib}} = \frac{2200}{30} = 73.3$

POWER GAIN $\quad A_p = A_i A_v = 90\ (73.3) = 6,600$

INPUT RESISTANCE $\quad R_{in} = \beta r'e = \beta h_{ib} = 90\ (30) = 2,700\Omega$

The potential advantage of accuracy using the h-parameters entails a more complicated and difficult analysis. The earlier Ebers-Moll model is much simpler to use. The h-parameters are listed in the transistor specification sheets prepared by the manufacturers and, therefore, it is necessary to know the methods of conversion.

TRANSISTOR EXPERIMENTS

In the many transistor experiments that follow, we will use the Ebers-Moll model and the simplified approximations based on this model, for our calculations. Because the common emitter configuration is used most often, and because there are many concepts to be discussed, the CE circuit will be the subject of the next six experiments as listed below.

Experiment 3 - Common Emitter (CE) Amplifier Operation
Experiment 4 - Emitter Degeneration
Experiment 5 - Transistor Bias Stability
Experiment 6 - Voltage Divider Biasing Amplifier Operation
Experiment 7 - I-O Impedance Measurements
Experiment 8 - Characteristic Curves

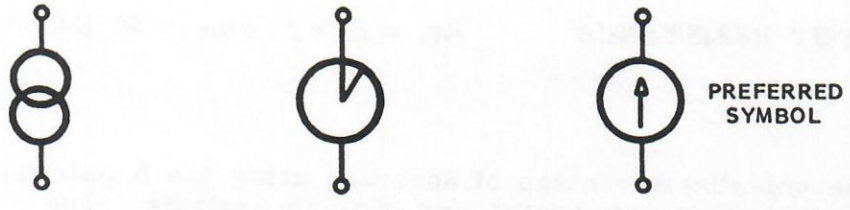
CONCLUSIONS

We have learned from this information sheet that:

1. Two of the models used to represent the equivalent circuit of a transistor are the Ebers-Moll model and the Hybrid Parameter model.

2. The Ebers-Moll model equivalent circuit is different for each configuration while the hybrid parameter model uses one form for all three configurations.

3. There are three symbols that may be used for a current generator.



4. The dynamic base-emitter junction resistance is defined as r'e and is equal to $25/I_E$.

5. The voltage amplification based on the Ebers-Moll equivalent circuit for the CE configuration is equal to $A_v = R_C/r'e$.

6. The input resistance for the CE configuration using the Ebers-Moll model is equal to $R_{in} = \beta r'e$.

7. In the h-parameter model there are four measured quantities: h_i, h_f, h_r and h_o.

8. The h-parameter system uses a single model for all three configurations by adding a second subscript to the measured quantities, e for CE, b for CB and c for CC.

9. Input Resistance, which is R_{in} in the Ebers-Moll model, is labeled h_{ie}, h_{ib} and h_{ic} in the hybrid model.

10. The Reverse Voltage Transfer ratio, h_r, is labeled h_{re}, h_{rb} and h_{rc}.

11. The Forward Current Transfer Ratio, which is alpha or beta in the Ebers-Moll model, is labeled h_{fe}, h_{fb} and h_{fc}.

12. The output resistance in the h-parameter model is given in admittance and defined as h_{oe}, h_{ob} and h_{oc}. To find the output resistance you take the reciprocal of h_o. Thus, $R_{out} = 1/h_o$.

13. The h-parameters can be converted to the r-parameters for simpler computations.

14. The h-parameter equivalents are:

    h_{fe} = beta h_{fb} = alpha

    $h_{ie} = \beta r'e$ $h_{ib} = r'e$

15. While h-parameter calculations are more precise than r-parameter calculations, the r-parameters are more than adequate because transistors are manufactured with a ± 20% tolerance.

16. An understanding of h-parameters are necessary because the manufacturer's transistor specification sheets give vital data in h-parameter form.

KEY TERMS

1. ACTIVE DEVICE

   A circuit component that can provide an increased output (amplification) of voltage, current and/or power when used in conjunction with a power supply. Typical active devices are transistors and vacuum tubes.

2. ADMITTANCE

   The ease with which a circuit conducts an ac current. It is the reciprocal of impedance and its unit is the mho, ℧ .

3. ALPHA (α)

   The unit of current gain in the CB configuration. It is the ratio of collector current to emitter current and is slightly less than 1.

4. BETA (β)

   The unit of current gain in the CE configuration. It is the ratio of collector current to base current and is normally between 50 and 200 or more.

5. COLLECTOR CHARACTERISTIC CURVE

   A graphic plot that shows how I_C varies with changes in V_{CE} given a fixed value of I_B.

6. CURRENT GAIN (A_i)

   The ratio of output signal current to input signal current.

7. CURRENT GENERATOR

   A generator with a current output independent of the load resistance connected across its output terminals.

8. CUT-OFF REGION

   The region of transistor operation where the base current is driven to zero resulting in no collector current and thus maximum collector voltage.

9. DYNAMIC JUNCTION RESISTANCE

The resistance of the junction as measured over a small portion of the junction characteristic curve. It is used to measure the base-emitter dynamic resistance, r'e.

10. EQUIVALENT CIRCUIT

A simplified arrangement of basic circuit components that reproduces the input and output characteristics of a more complex device.

11. h_{11}, h_{12}, h_{21}, h_{22}

Numerical equivalents of the h-parameters h_i, h_r, h_f, and h_o.

12. h_f

The h-parameter that indicates the forward current gain of a transistor. In the CB configuration it is h_{fb}, for CC it is h_{fc} and for CE it is h_{fe}.

13. h_i

The h-parameter that indicates the transistor input impedance. In the CB configuration it is h_{ib}, for CC it is h_{ic} and for CE it is h_{ie}.

14. h_o

The h-parameter that indicates the transistor output admittance. In its three forms, it is shown as h_{ob}, h_{oc}, and h_{oe}.

15. h_r

The h-parameter that indicates the reverse voltage transfer, that is, the amount of signal voltage that will appear at the input for a given signal voltage applied to the output. In its three forms, it is h_{rb}, h_{rc} and h_{re}.

16. h-PARAMETERS

Measurements made to produce an equivalent circuit of a transistor using short circuit and open circuit measurements, a hybrid system of measurements.

17. HYBRID MODEL

A model developed using a hybrid measuring system known as h-parameters.

18. INPUT RESISTANCE (R_{in})

The resistance seen by the input generator when connected to the transistor input circuit. Also called the Input Impedance. In h-parameters it is h_i.

19. LINEAR REGION

Also called the Active Region, it is the area of transistor amplifier operation where variations in collector current are directly proportional to variations in base current.

20. MODEL

The same as Equivalent Circuit; see 10 above.

21. OPERATING POINT

Also known as The Quiescent or Q Point, it is the steady state dc value of I_C and V_{CE} in a transistor circuit when no signal is applied.

22. OUTPUT ADMITTANCE (h_o)

An h-parameter measurement of the ease in which an ac current can flow in the transistor output circuit. The hybrid parameter measurement is h_o.

23. OUTPUT RESISTANCE (R_{out})

The resistance seen by the load connected across the transistor output circuit. R_{out} can be found by taking the reciprocal of h_o, $1/h_o$.

24. POWER GAIN (A_p)

The ratio of output power to input power. For a transistor amplifier, A_p is equal to the current gain multiplied by the voltage gain, given as $A_i \times A_v$.

25. r'e

Called R E PRIME, it is the ac resistance of the forward biased base-emitter junction. It is approximately equal to $25/I_E$ in mA.

26. r-PARAMETERS

Parameters used in the Ebers-Moll type models consisting of base resistance, r'b; emitter resistance, r'e; collector resistance, r'c and current gains of alpha (α) and beta (β).

27. REVERSE VOLTAGE TRANSFER RATIO (h_r)

See h_r, No. 15

28. SATURATION REGION

The region of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C.

29. SMALL SIGNAL AMPLIFIER

An amplifier where the swing in output current does not exceed 1/10 of the steady state dc collector current.

30. VOLTAGE GAIN (A_v)

The ratio of output voltage to input voltage.

$$A_v = V_{out} / V_{in}$$

ASSIGNMENT

Answer the following multiple choice questions.

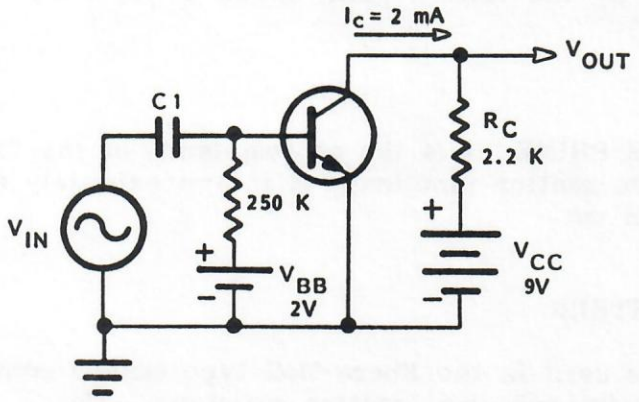


Figure 6 above refers to questions 1 to 5.

1. For the circuit shown in Figure 6, the value of r'e is approximately:

   a. 25 ohms.
   b. 12.5 ohms.
   c. 2.2 ohms.
   d. 2 ohms.

2. The value of r'e in Figure 6 is the same as:

   a. h_{fe}.
   b. h_{ie}.
   c. R_{in}.
   d. h_{ib}.

3. Given a base current of 8 μA, in Figure 6, the dc beta is closest to:

   a. 250.
   b. 200.
   c. 160.
   d. 100.

4. The transistor in Figure 6 has an alpha of:

   a. 100.
   b. 99.6
   c. 0.996.
   d. none of the above.

5. The circuit shown in Figure 6 has a voltage gain of:

   a. 2200.
   b. 176.
   c. 113.
   d. 13.5.

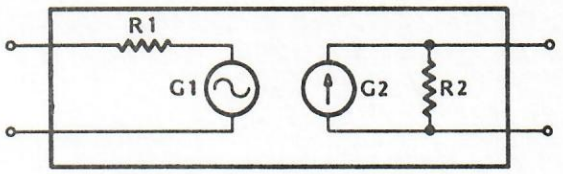


Figure 7 above refers to questions 6 to 11.

6. The equivalent circuit shown in Figure 7 is an:

   a. Ebers-Moll model.
   b. r-parameter model.
   c. h-parameter model.
   d. none of the above.

7. Resistance R1 in Figure 7 represents:

   a. h_i.
   b. h_f.
   c. h_r.
   d. h_o.

8. Resistance R2 in Figure 7 represents:

   a. r_i.
   b. re'.
   c. h_i.
   d. h_o.

9. Generator G1 in Figure 7 represents:

   a. β.
   b. h_{ie}.
   c. h_r.
   d. h_o.

10. Generator G2 in Figure 7 represents:

    a. I_{out}.
    b. h_i.
    c. V_{out}/r_i.
    d. h_r.

11. Given the output admittance of the equivalent circuit in Figure 7, the output resistance can be found from:

    a. V_{out}/β_{ib}
    b. h_{oe}/h_{ib}.
    c. $1/h_o$.
    d. any of the above.

12. The major drawback when using h-parameters is the:

    a. lack of accuracy.
    b. complex calculations.
    c. limitation to CE only.
    d. all of the above.

Common Emitter (CE) Transistor Amplifier Gain

Lesson No. 3

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 3, Common Emitter (CE) Amplifier Operation.

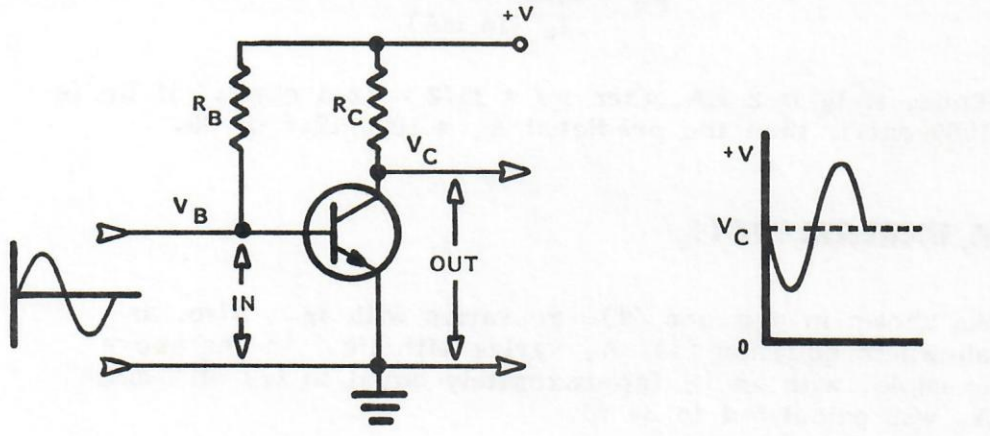
2. The simplest common emitter transistor circuit is biased from the +V source using a resistor in series with the base. The proper base current will set the collector current in the linear operating region.

3. The ac input signal voltage is amplified. The amount of voltage amplification, A_v, obtained is determined by the ratio of R_C to r'e.

4. Clipping may occur due to poor operating point selection or excessive signal input.

DISCUSSION

The most frequently used transistor amplifier circuit is the COMMON EMITTER configuration. The input voltage is applied to the base-emitter junction of the transistor and the output is taken from the collector-emitter junction. The emitter, as shown in Figure 1(a), is grounded and therefore common to both the input and output. The simplest version of the common emitter (CE) circuit uses only two resistors, as shown. We will experiment with this simple circuit.



(a) BASIC CE CIRCUIT (b) OUTPUT VOLTAGE

Figure 1 - Basic common emitter circuit and waveforms.

The base resistor, R_B in Figure 1(a) determines the base current, I_B, and the value of R_B is chosen to place the transistor in the linear operating region. The base current, in turn, determines the collector current, I_C, ($I_C = \beta I_B$). The collector current and the value of R_C determine the dc collector to ground voltage. This collector voltage, without the ac input signal, is called the OPERATING POINT.

VOLTAGE GAIN

The input ac signal shown in Figure 1(a) varies the base current which varies the collector current. The varying collector current causes a varying collector output voltage whose waveform, shown in Figure 1(b), is the same as the input waveform except that it is 180° OUT OT PHASE (inverted) and increased in amplitude (amplified).

The voltage gain, A_v, can be predicted by the formula presented in reference texts and a previous information sheet as:

$$A_v = \frac{R_C}{r'e} \qquad (1)$$

where r'e is the internal ac transistor base-emitter junction resistance. The value of r'e for "small signal voltages" can be approximated by the formula:

$$r'e = \frac{25}{I_E \text{ (in mA)}} \qquad (2)$$

Thus, if I_E is 2 mA, then r'e = 25/2 = 12.5 ohms. If R_C is 1000 ohms, then the predicted A_v = 1000/12.5 or 80.

A_v INCREASE WITH I_E

As shown in equation (2), r'e varies with I_E. Also, as shown in equation (1), A_v varies with r'e. In the above example, with an I_C (approximately equal to I_E) of 2 mA, A_v was calculated to be 80.

If I_C is increased from 2 mA to 4 mA, then:

$$r'e = \frac{25}{4} = 6.25 \qquad \text{and} \qquad A_v = \frac{R_C}{r'e} = \frac{1000}{6.25} = 160$$

Doubling I_C will thus double the gain, as will be shown in the experiment.

CE AMPLIFIER PHASE SHIFT

As noted earlier, the CE amplifier circuit produces an output voltage that is A_v times greater than the input voltage but, as shown in Figure 1, 180° out of phase with the input signal. This is often referred to as PHASE INVERSION and the gain is then written with a negative sign, as $A_v = -160$ to indicate phase inversion.

The 180° phase shift occurs through the following sequence, refering to Figure 1:

As the input signal, V_{in}, rises on its positive half cycle, the base current, I_B increases. An increase in I_B causes an increase in I_C. The increased I_C causes a greater voltage drop across R_C. This, in turn, reduces V_{CE}, the output voltage, causing it to swing in the negative direction as shown in Figure 1(b). As V_{in} rises, V_{out} falls, thus the term "inverted."

When the input signal swings negative, I_B decreases. This reduces I_C to reduce the voltage drop across R_C. A reduced voltage drop across R_C causes a rise in V_{CE}. This is shown as an increase in the positive direction in the output signal in Figure 1(b). Thus, we may conclude that, for the CE configuration, there is an inversion and, for a sine wave, this corresponds to a 180° phase difference between the input and output signals.

DISTORTION

It was shown earlier in Information Sheet 2, Characteristic Curves, that a proper choice of operating point is critical. The optimum point is in the center of the transistor's linear operating region. This allows the maximum undistorted output level from the amplifier. The choices of operating points are illustrated in Figure 2 for a typical load line plotted on the transistor collector curves.

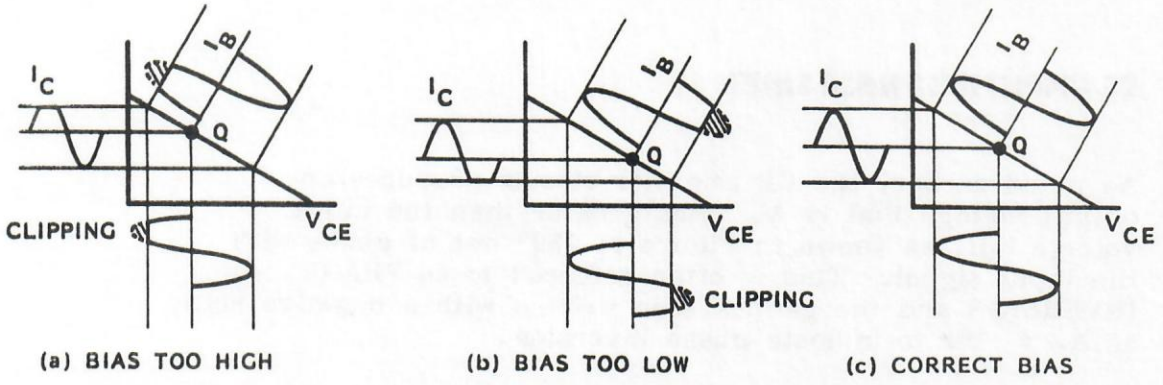


Figure 2 - Operating point versus output distortion.

A common method of locating the operating point in the linear region is by use of the transistor's CHARACTERISTIC CURVES and a LOAD LINE, both of which will be covered in later experiments. For now, you will adjust the circuit for various operating regions by biasing the transistor with the desired I_B resulting in an output V_{CE} and you will calculate the gain using equations (1) and (2).

KEY TERMS

1. COMMON EMITTER (CE)

   An amplifier circuit in which the emitter of the transistor is common to both the input and output circuits.

2. CUT-OFF REGION

   The region of transistor operation where the base current is zero resulting in no collector current and thus maximum output voltage, V_C.

3. LINEAR REGION

   The area of operation of a transistor amplifier where variations in collector current are directly proportional to variations in base current. The linear region is sometimes called the Active Region.

4. OPERATING POINT

   The dc condition of the transistor amplifier when the collector current and voltage are at rest, when no ac signal is applied to the transistor amplifier. The operating point is also called the "Quiescent" or Q point.

5. SATURATION REGION

   The region of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also, V_{CE} at saturation, is very low, frequently no more than several tenths of a volts.

6. VOLTAGE GAIN

   A measure of how much an amplifier stage increases the ac input signal level. It is expressed as:

$$A_v = V_{out} / V_{in}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. The phase relationship between the input and output signals of a common emitter amplifier is:

   a. zero degrees.
   b. 180 degrees.
   c. 360 degrees.
   d. variable with r'e.

2. Given an emitter current of 1.5 mA in a CE amplifier, the value of r'e in the transistor, is:

   a. 16.6 ohms.
   b. 37.5 ohms.
   c. 1.5 ohms.
   d. variable with changes in R_C.

3. A common emitter amplifier operated with an R_C of 1.4 K, a base resistor, R_B, of 470 K and a collector current of 2.2 mA, has a theoretical stage gain of:

   a. 335.7
   b. 470
   c. 123.2
   d. 14

4. A common emitter amplifier has a collector current of 4 mA, a base current of 50 μA, and a collector load resistor of 1,000 ohms. The transistor beta is approximately:

   a. 1,000.
   b. 80.
   c. 50.
   d. 40.

5. When the base bias current is high, the result is:

   a. a high stage gain.
   b. a low stage gain.
   c. a 90° phase shift.
   d. clipping of the output signal.

Common Emitter (CE) Amplifier Operation

3

OBJECTIVES

When you finish this experiment you will be able to:

1. Recognize a common emitter transistor amplifier circuit and know where to measure the input and output signal voltages.
2. Adjust the base bias current to obtain any desired collector current and dc operating point.
3. Calculate the theoretical expected voltage gain.
4. Vary the dc base bias and ac input signal amplitude to observe distortion of the output signal.
5. Determine the maximum undistorted output level of an amplifier stage.
6. Measure the amplifier gain at various collector currents and understand that gain varies with different collector currents.
7. Describe the phase relationship between the input and output signals of a CE amplifier.

REFERENCE

CES Lesson J1-3, Common Emitter (CE) Transistor Amplifier Gain

BACKGROUND

1. The common emitter (CE) amplifier is the most often used circuit because it has both voltage and current gain.
2. The operating point must be placed as close as possible to the center of the linear operating area so as to allow the largest possible value of undistorted output voltage swing between saturation and cut-off in the collector circuit.
3. The input and output signals in a CE configuration are always 180° out of phase with each other.

4. The theoretical voltage gain is determined from $A_v = R_C/r'e$ and the actual voltage gain is found from the measured results, $A_v = V_{out}/V_{in}$.

5. The amplifier gain will vary when I_E (and thus I_C) is changed as this changes the value of r'e. Increases in I_E lower r'e, increasing voltage gain ($r'e = 25/I_e$ in mA).

6. This Experiment, No. 3, is in four parts:

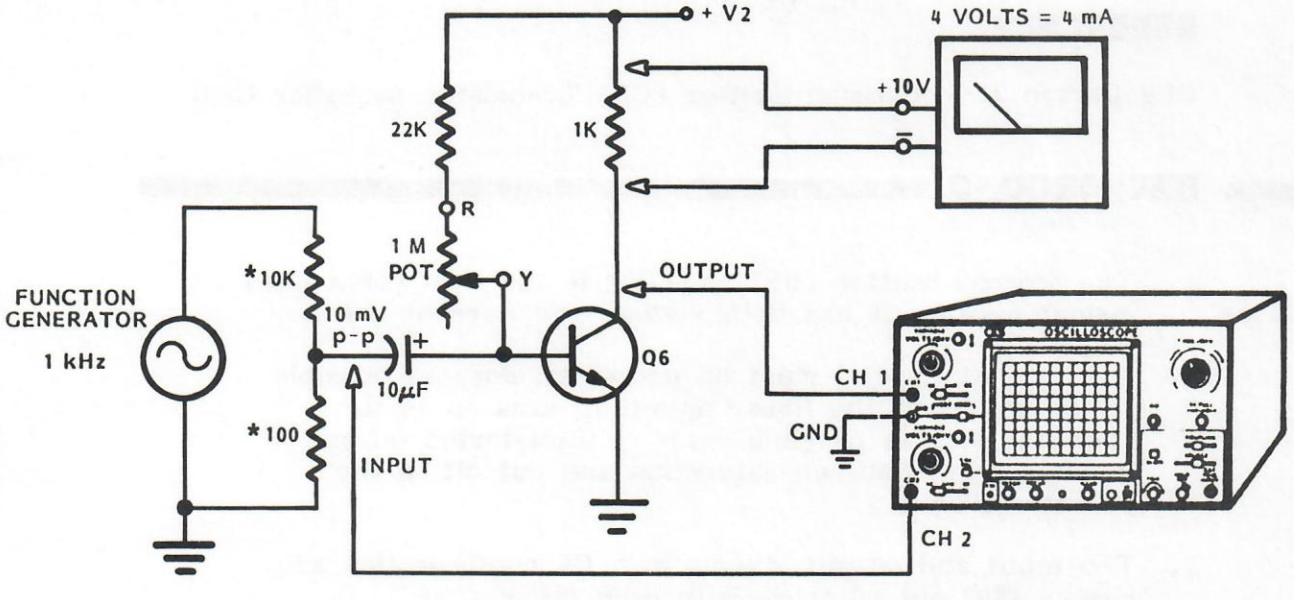
   3.1 Voltage Gain
   3.2 Amplifier Distortion
   3.3 Gain Variation with I_C Variations
   3.4 Gain Variation with R_C Variations

PROCEDURE

3.1 VOLTAGE GAIN

In this first part of the experiment, we will measure the voltage gain of a common emitter (CE) amplifier and compare it to the theoretical predicted value.

1. Wire the CE amplifier circuit shown in Figure 1.



*NOTE: In Ed-Lab 651 models with HI-LO switch for sine amplitude, set at LO and omit 10 K and 100 ohm resistors and connect the amplifier input directly to the sine jack on this and all subsequent experiments.

Figure 1 - Common emitter amplifier EXPERIMENT.

2. Set the oscilloscope CH 1 (Output) at 0.5 V/DIV and position the trace near the top of the screen.

3. Set the oscilloscope CH 2 (Input) at 10 mV/DIV and position the trace near the bottom of the screen.

4. Adjust the input ac signal to zero and adjust the 1 meg bias pot for an I_C of 4 mA indicated by a 4 volt reading on the dc meter across R_C.

5. Set the input frequency to 1 kHz and adjust the input signal to 10 mV p-p (1 cm on the CH 2 display).

6. Measure and record V_{out} ac p-p from the CH 1 display and record it below.

$V_{in\ ac}$ = 10 mV p-p	$V_{out\ ac}$ = V p-p

7. Compare the input and output signals displayed on the oscilloscope. What is their phase relationship?

_____

_____

8. Calculate the actual stage gain from the measured values using the formula $A_v = V_{out} / V_{in}$.

MEASURED GAIN	A_v =

9. Calculate the theoretical voltage gain based on the formulas below:

$$r'e = \frac{25}{I_E} = \frac{25}{4} = 6.25$$

$$A_v = \frac{R_C}{r'e} = \frac{1000}{6.25}$$

THEORETICAL VOLTAGE GAIN	A_v =

You can conclude from the above that in a CE amplifier, the actual or measured voltage gain, A_v, is determined from V_{out} / V_{in}. The theoretical gain is determined from

$A_v = R_C/r'e$ and may differ by ± 20% of the measured gain due to variations in transistors, temperature and other factors. It was also observed that the input and output ac waveforms are 180° out of phase with each other.

3.2 AMPLIFIER DISTORTION

In this part of the experiment, we will vary the base bias and input signal amplitude. We will observe the distortion of the output signal as the transistor moves out of the linear region into the cut-off and saturation regions.

10. Set the CH1 Input Switch to GND and adjust the Position control to move the trace down to the zero line at the bottom of the screen. This will enable us to see the collector voltage referenced to ground at the bottom of the scale.

    Move the 10 mV input signal, CH2, to the top of the screen.

11. Move the CH1 Input Switch to DC and the vertical scale should be set at 2 V/DIV. What do you observe on the CH1 display (on the bottom of the screen)?

12. Vary the 1 Meg bias pot in both directions. What happens to the output signal?

13. Reset the bias control (1 Meg pot) for a 4 mA collector current (meter at 4 volts). Increase and decrease the input ac signal voltage level and observe the output signal waveform (on the bottom of the screen). You may use the full ac output of the Function Generator to see a vivid display of saturation and cut-off. What happens?

14. Increase the input ac signal level with I_C at 4 mA until the output just begins to distort and back off slightly for an undistorted signal. What is the maximum input signal and undistorted output ac p-p voltage?

MAXIMUM INPUT	$V_{in\ max}$ = V p-p
MAXIMUM UNDISTORTED OUTPUT	$V_{max\ und.}$ = V p-p

You can conclude from the above that if the bias is moved away from the middle of the linear region, the output may become distorted. Also, if the input signal is excessive, the output will become distorted. The maximum p-p undistorted output signal can approach but never equal or exceed V_{CC} which in our circuit is +V2 and is 9 volts.

3.3 GAIN VARIATION WITH I_C

In this part of the experiment we will vary the collector current, I_C, and observe its effect on the voltage gain, A_v. We expect the gain to increase as I_C gets larger because r'e gets smaller.

15. Complete the first line of Table 1 with the data derived in step 6 for an I_C of 4 mA or you can repeat this step.

SET		DATA	
I_C (mA)	V_{in} (mV p-p)	V_{out} (V p-p)	A_v (measured)
4	10		
3	10		
2	10		
1	10		

TABLE 1 - Gain versus I_C for the circuit of Figure 2.

16. Set I_C at 3 mA. Set the input at 10 mV p-p again. Measure and record the p-p output voltage in Table 1. Calculate and enter the stage gain. Set I_C at 2 mA, measure the stage gain and enter the results in Table 1.

17. Change the 22K resistor in series with the 1 meg bias pot to 1 meg so that we can get a lower base current. Adjust the 1 meg pot for an I_C of 1 mA. Measure $V_{out\ p-p}$, calculate A_v, and enter the data in Table 1.

18. Plot the results from Table 1 on the graph in Figure 2. Note that the theoretical values of Av are already plotted on the graph based on $A_v = 40\ I_C$, which is derived as shown adjacent to the graph.

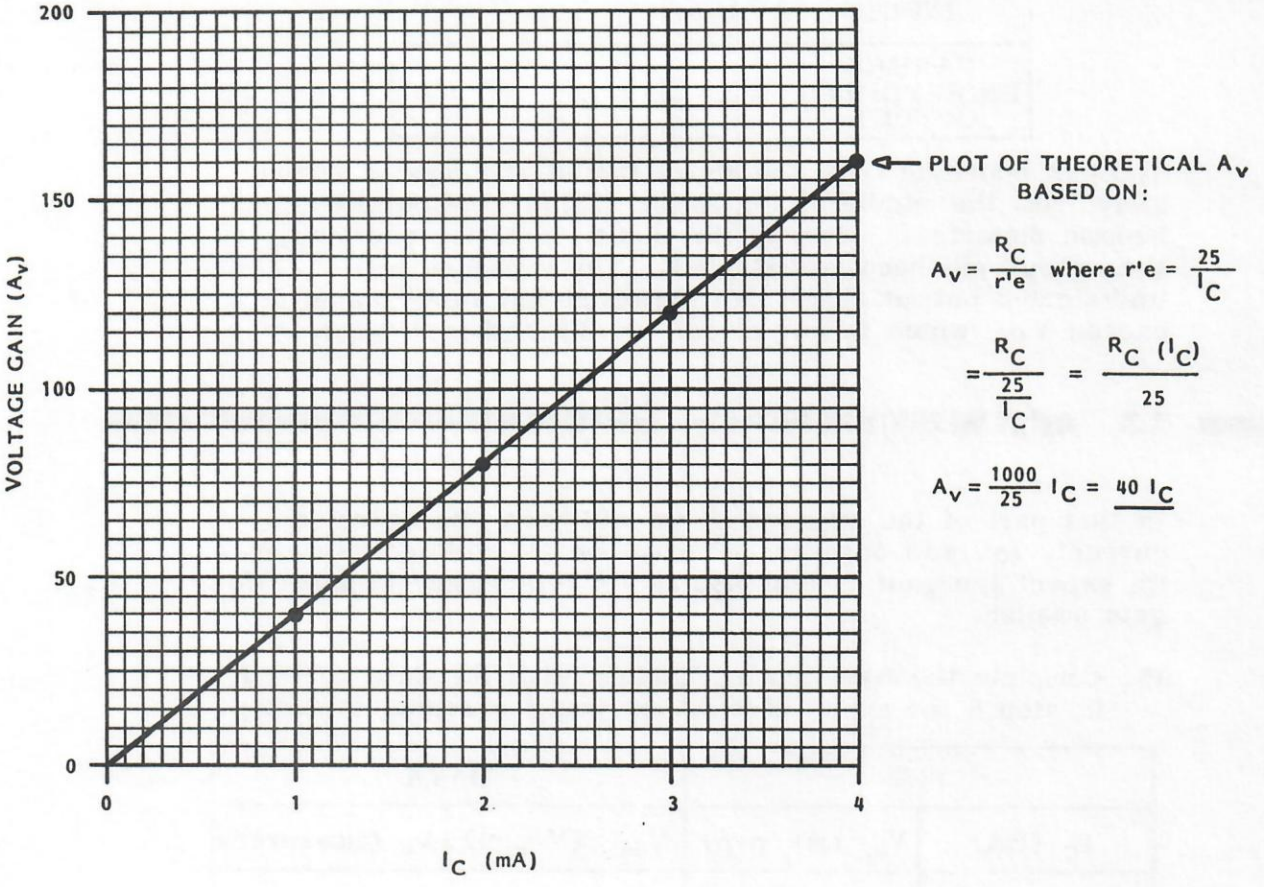


Figure 2 - Plot of theoretical and actual gain for different values of I_C.

You can conclude from the above that both the theoretical and actual gains increase with I_C. The actual gain is not exactly equal to the theoretical gain because the formula for r'e is only an approximation. Some reference texts use a number other than 25 (typically 30) in the formula for r'e.

3.4 GAIN VARIATION WITH R_C

In this part of the experiment we will show the effect of a different R_C value upon the voltage gain of the amplifier. We expect the gain to increase as R_C increases because of the formula for A_v.

19. Replace the 1K collector resistor with a 10K resistor.

    Add a second 1 megohm resistor in series with the 1 meg bias pot for a total of 3 megohms. Adjust the pot for a voltage drop of 7 volts across the new collector resistor, R_C. This gives us an I_C of 0.7 mA. You may have to vary the base resistance to obtain a 0.7 mA current.

20. Set V_{in} at 10 mV p-p; measure and record $V_{out\ p\text{-}p}$.

OUTPUT WITH R_C = 10 K	V_{out} = V p-p

21. Calculate the measured gain from:

$$A_v = \frac{V_{out\ p\text{-}p}}{V_{in\ p\text{-}p}} = \frac{(\quad)}{10\ mV}$$

MEASURED GAIN R_C = 10 K	A_v =

22. Calculate the theoretical gain from:

$$A_v = \frac{R_C\ (I_C)}{25} = \frac{10{,}000\ (0.7)}{25}$$

THEORETICAL GAIN R_C = 10 K	A_v =

Compare the theoretical and measured voltage gains from steps 21 and 22 above.

_____

_____

How does the measured gain for 10 K compare with the measured gain for 1 K (step 8)?

_____

_____

23. Determine the maximum allowable input signal before the output begins to distort and record the value below.

MAXIMUM ALLOWABLE INPUT; R_C = 10 K	$V_{in\ max}$ = mV p-p

How does the maximum allowable input signal for the 10 K compare with the maximum allowable input signal for 1 K (step 14)?

You may conclude from the above that when a high value collector load resistance and a high dc voltage drop across this resistor are used, a very high gain is obtained. This does, however, lower the maximum allowable input signal voltage before distortion occurs. This simple CE circuit is acceptable and is popular when very low input ac signals are to be amplified.

CONCLUSIONS

We have learned from this experiment that:

1. The most frequently used transistor amplifier configuration is the common emitter (CE).

2. In the common emitter circuit, the emitter is common to both the base and collector circuits.

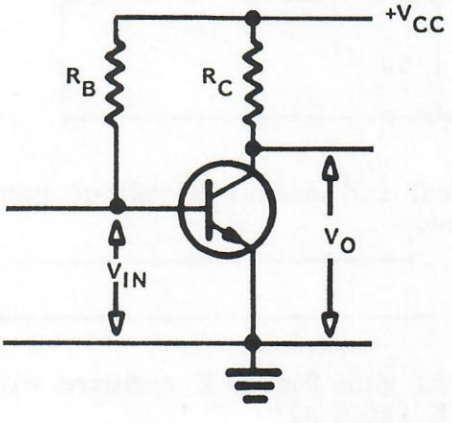


Figure 3 - CE circuit.

3. In the CE circuit of Figure 3, the base current is determined by V_{CC} and R_B where:

$$I_B = \frac{V_{CC}}{R_B} \text{ or more accurately, } I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

4. The collector current, I_C, in the circuit of Figure 3, is set by I_B and beta where:

$$I_C = I_B$$

5. The theoretical voltage gain for the circuit of Figure 3 is given by:

$$A_v = \frac{R_C}{r'e} \text{ where } r'e = \frac{25}{I_C} \text{ (where } I_E \cong I_C)$$

Substituting:

$$A_v = \frac{R_C}{\frac{25}{I_C}} = \frac{(R_C)(I_C)}{25}$$

6. The measured voltage gain for the circuit of Figure 3 is given by:

$$A_v = \frac{V_{out}}{V_{in}}$$

7. The higher the collector current operating point the greater the gain will be.

8. The output signal ac sine waveform is 180° out of phase with the input signal waveform or we say it is "inverted."

9. An increased value of R_C results in a higher voltage gain.

10. Distortion or clipping will occur when the operating point of the transistor is shifted out of the linear area or the input signal is too great causing the transistor to go into cut-off and saturation.

11. When the CE amplifier is biased so that V_{CE} is one half of V_{CC}, the maximum peak-to-peak undistorted output will almost equal V_{CC}.

KEY TERMS

1. COMMON EMITTER (CE)

   An amplifier circuit in which the emitter of the transistor is common to both the input and output circuits. The input is at the base and the output is at the collector.

2. CUT-OFF REGION

   The region of transistor operation where the base current is zero resulting in no collector current and thus maximum V_C.

3. LINEAR REGION

   The region of operation of a transistor amplifier where variations in collector current are directly proportional to variations in base current. The linear region is sometimes called the Active Region.

4. OPERATING POINT OR Q POINT

   The dc condition of the transistor amplifier when the collector current and voltage are at rest, when no ac signal is applied to the transistor amplifier. The operating point is also called the "Quiescent" or Q point.

5. SATURATION REGION

   The region of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also, V_{CE} is very low, frequently no more than several tenths of a volt.

6. VOLTAGE GAIN

   A measure of how much an amplifier stage can increase the input signal voltage level. It is expressed as:

$$A_v = V_{out} / V_{in}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. In the CE configuration, the _____ is common to the _____ circuit.

   a. collector; input
   b. emitter; input and output
   c. base; output and V_{CC}
   d. none of the above.

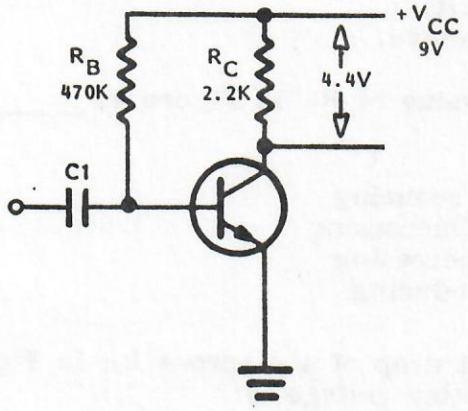


Figure 4 above refers to questions 2 to 12.

2. In the circuit of Figure 4, the emitter current, neglecting I_B, is approximately:

   a. 2 mA
   b. 2.2 mA
   c. 4.4 mA
   d. 6.6 mA

3. The transistor in the circuit of Figure 4 has an r'e of:

   a. 12.5 ohms.
   b. 25 ohms.
   c. 50 ohms.
   d. insufficient data to compute.

4. The voltage gain of the circuit shown in Figure 4 is:

   a. 37.6
   b. 44
   c. 80
   d. 176

5. The value of base current in the circuit of Figure 4:

   a. is set by the value of R_B.
   b. determines the voltage drop across R_C.
   c. determines the voltage from collector to emitter.
   d. all of the above.

6. In the circuit of Figure 4, a shift in the base current may cause:

   a. distortion to occur.
   b. operation in the cut-off region.
   c. operation in the saturation region.
   d. all of the above.

7. The function of capacitor C1 in Figure 4 is to prevent the:

   a. 470K resistor from loading the generator output.
   b. dc resistance of the input source from upsetting the base bias.
   c. generator ac signal from affecting the output collector voltage.
   d. all of the above.

8. Reducing the value of R_B in Figure 4, _____ I_B thus _____ V_C.

   a. increases; reducing
   b. increases; increasing
   c. reduces; increasing
   d. reduces; reducing

9. Given a voltage drop of 4.4 across R_C in Figure 4, the collector to emitter voltage is:

   a. 4.25 V.
   b. 4.6 V.
   c. 5 V.
   d. 9 V.

10. The maximum undistorted output voltage for Figure 4 can be achieved when the:

    a. value of r'e is kept high.
    b. value of R_C is low.
    c. operating point is in the center of the linear operating region.
    d. operating point is in the saturation region.

11. As the value of I_E is increased in the circuit of Figure 4, the:

    a. value of r'e drops.
    b. amplifier gain decreases.
    c. measured gain will be more than the theoretical gain.
    d. all of the above.

12. The output signal voltage for Figure 4 will be _____ than the input voltage and _____ phase with the input signal.

    a. less; in
    b. less; 180° out of
    c. greater; 180° out of
    d. greater; in

Emitter Degeneration Effects

Lesson No. 4

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 4, Emitter Degeneration.

2. The gain of a CE amplifier is a function of $R_C/r'e$. Because r'e prime is so variable with emitter current and temperature, A_v can differ considerably from its theoretical value.

3. The addition of a "swamping resistor" in the emitter circuit stabilizes the gain but also reduces the gain.

4. The ideal operating point is obtained when I_C is set in the center of the transistor's linear operating region.

DISCUSSION

It was derived in the earlier Information Sheet on Transistor Models and shown in Experiment 3 that the voltage gain of the common emitter amplifier can be determined by the emitter resistance, r'e and the value of the collector resistance, R_C. The values of r'e and A_v were expressed as:

$$r'e = \frac{25}{I_E \text{ (in mA)}} \quad (1)$$

$$A_v = \frac{R_C}{r'e} \quad (2)$$

The voltage gain, A_v, increased as the emitter current increased. If I_E is doubled, theoretically the gain will double. The gain, however, is not totally predictable as it does not quite double.

The value of r'e in a transistor varies with several factors. First, as shown in equation (1) above, r'e varies with the emitter current or base bias which is not always constant. Second, r'e varies with temperature and third, r'e varies from transistor to transistor of the same type. As a result, the voltage gain obtained from a CE amplifier circuit such as shown in Figure 1(a) can vary widely.

SWAMPING RESISTORS

Because the value of r'e is so variable and because the stage gain can be so high, good design procedure requires that a series resistor be placed in the emitter circuit as shown in Figure 1(b).

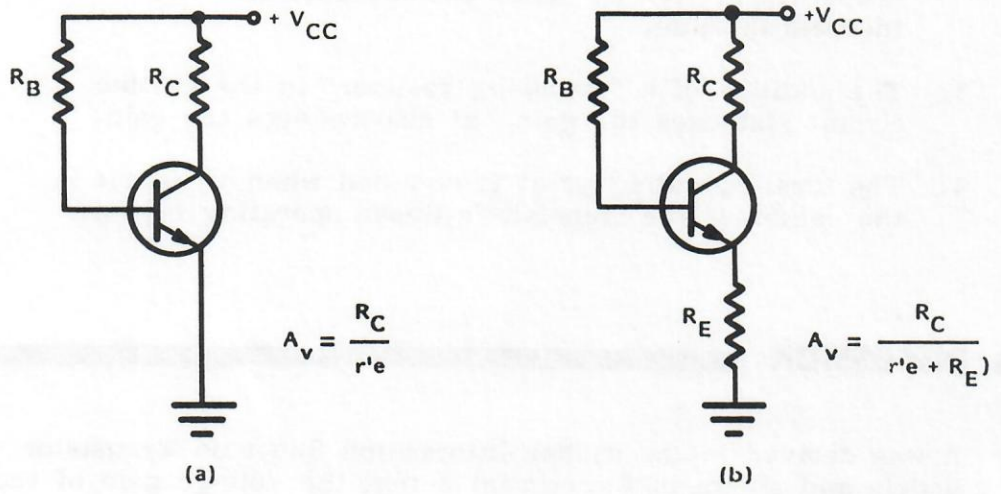


Figure 1 - Two typical common emitter amplifier circuits.

The resistor, in Figure 1(b), labelled R_E is the EMITTER SWAMPING RESISTOR because it "overpowers" or "swamps" the variations in r'e. This minimizes the effects of changes in r'e on the voltage gain. Using the emitter resistor, R_E, the gain is now:

$$A_v = \frac{R_C}{(r'e + R_E)} \qquad (3)$$

If R_E is made large enough, it will control the gain rather than r'e. If R_C is 2.2K and R_E is 200 ohms and r'e is 10 ohms, then:

$$A_v = \frac{R_C}{(r'e + R_E)} = \frac{2200}{10 + 200} = A_v = \underline{10.5}$$

Without the swamping resistor, the gain would be:

$$A_v = \frac{R_C}{r'e} = \frac{2200}{10} = A_v = \underline{220}$$

Still another problem with the circuit of Figure 1(a) is that, because r'e is normally low, the stage gain is very high. For example, if r'e is 10 ohms and R_C is 2.2K, A_v equals 2200/10 = 220. This high gain limits the level of the input signal, before output distortion occurs, to no more than approximately 0.03 volts p-p. Many input signals are greater than 0.03 volts and so lower stage gains must be used to avoid distortion due to excessive input signal.

With the swamping resistor in the circuit, the gain will now barely change with variations in r'e. Consider the variations in gain when r'e changes by 5 ohms in either direction from 10 ohms to 5 and 15 ohms.

For r'e = $\underline{5\ \Omega}$ $\quad A_v = \dfrac{R_C}{(r'e + R_E)} = \dfrac{2200}{(15 + 200)} = \underline{10.73}$

For r'e = $\underline{15\ \Omega}$ $\quad A_v = \dfrac{R_C}{(r'e + R_E)} = \dfrac{200}{(15 + 200)} = \underline{10.23}$

As seen from the above, the gain of the amplifier changes very little due to changes in r'e when the swamping resistor, R_E, is in the circuit. Also, with the lower gain of 10.5 and an assumed output swing in V_C of 7 volts, the input signal that can be accomodated, is now:

$$A_v = \frac{V_{out}}{V_{in}} \qquad 10.5 = \frac{7}{V_{in}} \qquad V_{in} = \frac{7}{10.5} = \underline{0.66\ V\ p\text{-}p}$$

This represents an rms input level of 0.24 volts. We can now accomodate higher input signal voltages by using an emitter resistor, R_E.

LINEAR OPERATING REGION

When operating at the Q point, the ideal collector-to-emitter voltage is equal to:

$$V_{CE\ IDEAL} = \frac{(V_{CC} - V_{RE})}{2}$$

where V_{RE} is the dc voltage across the emitter resistor.

With V_{CE} at one half of the available voltage ($V_{CC} - V_{RE}$), it is now possible for V_{CE} to swing equally in both the positive and negative directions. This allows for the maximum peak-to-peak output voltage before distortion occurs. If the operating point is moved above or below this ideal value, the output signal will start to clip sooner, thus reducing the MAXIMUM UNDISTORTED OUTPUT voltage level. This also reduces the maximum allowable input signal before distortion occurs.

KEY TERMS

1. CUT-OFF REGION

   The region of transistor operation where the base current is driven down to zero resulting in no collector current and thus maximum V_{CE}.

2. DEGENERATION

   A loss or deterioration of a function such as amplifier gain. Often deliberately introduced by feeding a portion of the collector or emitter signal back to the input in such a way that it cancels a part of the input signal.

3. DISTORTION

   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is usually the result of operating in the non-linear areas of a transistor.

4. EMITTER SWAMPING RESISTOR

   A resistor placed in series with the emitter that is usually 10 times greater in value than r'e. It minimizes the effect on A_v for any changes in r'e.

5. LINEAR OPERATING REGION

   The area of transistor operation where variations in collector current are directly proportional to variations in base current. This linear area is sometimes referred to as the Active Region.

6. OPERATING POINT

   The collector current, at rest, with no signal applied to the transistor amplifier. In an analog amplifier the operating point should be located in the center of the linear region. It is also known as the Q or Quiescent Point.

7. r'e

Called R E PRIME, it is the ac resistance of the forward biased base-emitter junction. This ac resistance is approximately equal to $25mV/I_E$ in mA.

8. SATURATION REGION

The region of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also, V_{CE} is very low, frequently no more than several tenths of a volt.

9. SWAMPING RESISTOR

See No. 4, Emitter Swamping Resistor.

10. VOLTAGE GAIN

A measure of how much an amplifier can increase the input signal voltage level. It is expressed as:

$$A_v = V_{out} / V_{in}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. Given a CE transistor amplifier in which the emitter is directly grounded, r'e equals 14 ohms and R_C is 2.7K, the gain:

   a. will vary with temperature.
   b. is 193, theoretically.
   c. will vary with I_E.
   d. all of the above.

2. The addition of a resistance in the emitter circuit, called R_E, causes the circuit gain to:

   a. drop.
   b. be stabilized against changes in I_C.
   c. be stabilized against changes in temperature.
   d. all of the above.

3. When selecting an operating point in a CE circuit that has a 1 volt drop across the emitter resistor and a V_{CC} of 15 volts, the ideal V_{CE} operating point is:

   a. 15 volts.
   b. 14 volts.
   c. 7 volts.
   d. 1 volt.

4. Operating at the ideal Q point allows:

   a. no variation in gain due to temperature changes.
   b. the maximum peak-to-peak output voltage swing.
   c. a smaller p-p input signal swing.
   d. all of the above.

5. Moving away from the ideal operating point, in either direction, in a CE amplifier, causes:

   a. output signal clipping.
   b. reduced gain.
   c. reduced distortion.
   d. greater operating efficiency.

Emitter Degeneration 4

OBJECTIVES

When you finish this experiment you will be able to:

1. Add an emitter swamping resistor to the common emitter amplifier circuit to minimize the effect of a varying r'e.
2. Calculate the amplifier voltage gain with the emitter swamping resistor in the circuit.
3. Calculate the maximum allowable ac input signal before the amplifier is overdriven.
4. Observe the effect on the output signal waveshape when the amplifier is overdriven.
5. Locate the ideal operating point to provide the maximum undistorted output signal.

REFERENCE

CES Lesson J1-4, Emitter Degeneration Effects

BACKGROUND

1. The transistor amplifier has a voltage gain whereby a small input signal voltage to the base circuit will produce a higher output signal voltage at the collector circuit.
2. The voltage gain, A_v, of the CE amplifier is a function of $R_C/r'e$.
3. An emitter swamping resistor is added to the circuit to stabilize A_v and reduce the gain to where the amplifier does not overload easily.
4. The operating point is adjusted by varying the base bias to obtain the ideal setting and also to observe the effect of improper bias.
5. This Experiment No. 4 is in three parts:

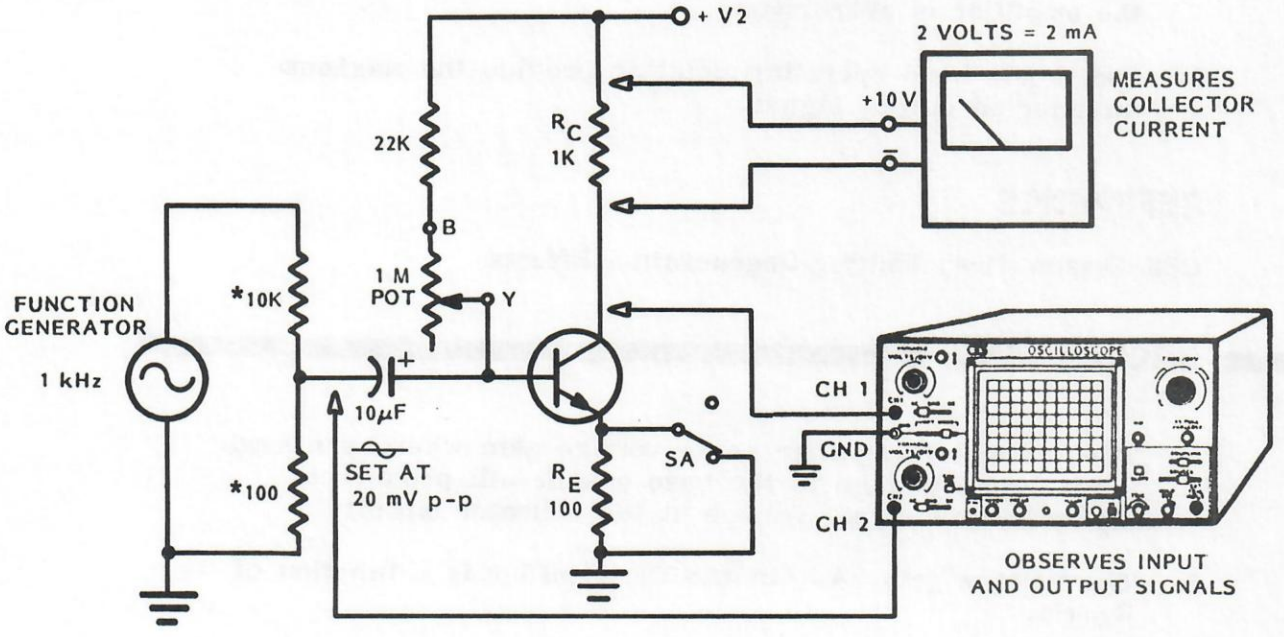
   4.1 Stage Gain Measurements
   4.2 Gain Variations With I_C and R_E
   4.3 Linear Operating Region

PROCEDURE

4.1 STAGE GAIN MEASUREMENTS

In this first part of the experiment, we will construct a common emitter amplifier and measure and calculate the stage gain with the emitter directly grounded and then with a 100 ohm emitter "swamping" resistor.

1. Wire the circuit shown in Figure 1.



* NOTE: If a HI-LO output switch is on your trainer, omit these two resistors, connect directly to the sine output and place the HI-LO switch to LO.

Figure 1 - Common emitter amplifier with degeneration; EXPERIMENT.

2. Set the Function Generator frequency to 1 kHz and the ac input signal voltage level to zero volts.

   Place switch SA in the DOWN position to remove the resistor, R_E, 100 ohms, from the emitter circuit, thus grounding the emitter directly. Now, adjust the 1 meg bias pot for a collector current of 2 mA (a 2 volt reading on the meter).

3. To measure the voltage gain, increase the ac input signal level to 20 mV p-p as shown on the CH 2 display.

4. This first test is a repeat of previous procedures to measure the gain of a CE stage. Measure $V_{out\ p\text{-}p}$ from the CH 1 display and record it below.

OUTPUT WITH $V_{in\ p\text{-}p}$ AT 20 mV	V_{out} = V p-p

5. Calculate the stage gain using the measured values as shown below.

$$A_v = \frac{V_{out\ p\text{-}p}}{V_{in\ p\text{-}p}} = \frac{(\quad)}{0.02}$$

MEASURED VOLTAGE GAIN	A_v =

6. The theoretical gain for the CE amplifier, without the swamping resistor, as described in the previous experiment, is:

$$A_v = \frac{R_C}{r'e} \qquad \text{where } r'e = \frac{25}{I_C}$$

$$\text{Thus } A_v = \frac{1000}{25/2}$$

THEORETICAL VOLTAGE GAIN	A_v =

The actual or measured gain is close to the theoretical gain but not exact because of temperature differences and other factors in the approximation for r'e.

7. Place switch SA in the UP position thus adding R_E, 100 ohms, in series with the emitter circuit. Readjust the 1 meg pot to provide an I_C of 2 mA.

8. Measure the new p-p output voltage for the same 20 mV p-p input and record V_{out} below. Then calculate the voltage gain, A_v.

V_{out} WITH R_E IN CIRCUIT; V_{in} = 20 mV	V_{out} = V p-p

MEASURED VOLTAGE GAIN	A_v =

9. Calculate the theoretical stage gain, with the swamping resistor, from:

$$A_v = \frac{R_C}{(r'e + R_E)} = \frac{R_C}{(25/I_E) + R_E} \quad \text{(where } I_E \cong I_C = 2\text{mA)}$$

$$A_v = \frac{1000}{(25/2) + 100}$$

THEORETICAL VOLTAGE GAIN	A_v =

Are the measured and theoretical gains of the amplifier with the 100 ohm emitter resistor, R_E, in the circuit, close in value?

Is the gain of the circuit with the emitter resistor, R_E, less than the gain without R_E?

You may conclude from the above that the addition of an emitter swamping resistor, R_E, reduces the stage gain considerably. This is useful if we desire to reduce the gain when we have a large input signal.

4.2 GAIN VARIATIONS WITH I_C AND R_E

In this part of the experiment we will vary the collector current, I_C, and observe its effect on the voltage gain when the emitter resistor, R_E, is in the circuit. Recall, that without R_E, as in Experiment 3, A_v increased with a rise in I_C.

10. Enter the data collected in step 8 in Table 1 on the first line for an I_C of 2 mA.

11. Leave V_{in} unchanged at 20 mV p-p and increase I_C to 3 mA (3 volts on the meter).

    Determine $V_{out\ p\text{-}p}$ from the CH 1 display and record it in Table 1. Then repeat the above procedure for collector currents of 4, 5 and 6 mA and enter the data in Table 1.

SET		READ	CALCULATE
I_C (mA)	$V_{in\ p\text{-}p}$	$V_{out\ p\text{-}p}$	$A_v = V_{out} / V_{in}$
2	20 mV		
3	20 mV		
4	20 mV		
5	20 mV		
6	20 mV		

TABLE 1 - Gain versus I_C for the circuit of Figure 3 with the 100 ohm emitter resistor, R_E.

12. Calculate the voltage gain of the amplifier for each value of collector current as directed in Table 1.

    How does the gain of the amplifier vary with changes in I_C when there is an emitter swamping resistor in the circuit?

    _____

    _____

You may conclude from the above that when an emitter swamping resistor is used in the common emitter circuit, the gain is not only reduced but no longer varies with changes in I_C. This is a great advantage in stabilizing the gain performance of the amplifier.

4.3 LINEAR OPERATING REGION

In this part of the experiment we will observe the effect of setting the operating point mid-way between saturation and cut-off. This is the ideal operating point for producing the maximum undistorted peak-to-peak output voltage.

13. The ideal collector to emitter voltage is one half V_{CC} (+V2 in our circuit) less any voltage drop across R_E (if R_E is in the circuit). Expressed mathematically:

$$V_{CE\ IDEAL} = \frac{V_{CC} - V_{RE}}{2}$$

To obtain half the voltage across the load and half across the transistor, I_C will be set at 4.28 mA and the voltage drop across R_E will be 0.428 volts ($100 \times 4.28 \times 10^{-3}$). Thus, the ideal V_{CE} is:

$$V_{CE\ IDEAL} = \frac{9 - 0.428}{2} = \underline{4.286\ V}$$

The remaining 4.286 volts will appear across R_C.

14. In order to provide a larger input voltage, move the ac input lead from the junction of the 100 ohm and 10K resistors to the full output of the Function Generator. If your Ed-Lab 651 has a HI-LO switch, simply move the switch to the HI position.

    Be sure switch SA is UP for R_E, 100 ohms, to be in the circuit.

    Adjust I_C as close to 4.3 mA as possible (a 4.3 volt reading on the meter across R_C) using the 1 meg bias pot.

15. Increase the ac input signal voltage to obtain the maximum undistorted output signal. Record the maximum undistorted p-p output voltage below.

MAXIMUM UNDISTORTED V_{out} WITH I_C = 4.3 mA	V_{out} = V p-p

16. Rotate the 1 meg bias pot slightly CW and then CCW. Observe and describe the effect this has on the output waveform.

_____

_____

_____

You may conclude from the above that when the bias is set correctly, the maximum undistorted peak to peak output signal voltage will be available. You will have also observed that any deviation from this optimum operating point will introduce distortion or require that the maximum allowable input level be reduced.

CONCLUSIONS

We have learned from this experiment that:

1. The gain of a common emitter amplifier without a swamping resistor is equal to $R_C/r'e$.

2. The introduction of an emitter swamping resistor to the CE circuit reduces the stage gain and makes A_v relatively independent of changes in r'e.

3. The gain of a CE amplifier with an emitter swamping resistor equals $R_C/(R_E + r'e)$.

4. Where the CE amplifier is operated without an emitter swamping resistor, the gain is so high that very low level ac input signals may cause overdrive.

5. The maximum allowable ac signal input voltage is determined from $V_{in\ max} = V_{out\ max} / A_v$.

6. When an emitter swamping resistor is used, the voltage gain remains almost constant with changes in I_E.

KEY TERMS

1. CUT-OFF REGION

   The region of transistor operation where the base current is driven down to zero resulting in no collector current and thus maximum V_{CE}.

2. DEGENERATION

   A loss or deterioration of a function such as amplifier gain. Often deliberately introduced by feeding a portion of the collector or emitter signal back to the input in such a way that it cancels a part of the input signal.

3. DISTORTION

   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is usually the result of operating in the non-linear areas of a transistor.

4. EMITTER SWAMPING RESISTOR

   A resistor placed in series with the emitter that is usually 10 times greater in value than r'e. It minimizes the effect on A_v for any changes in r'e.

5. LINEAR OPERATING REGION

   The region of transistor operation where variations in collector current are directly proportional to variations in base current. This linear region is sometimes referred to as the Active Region.

6. OPERATING POINT

   The collector current and voltage, at rest, with no signal applied to the transistor amplifier. In an analog amplifier the operating point should be located in the center of the linear region. Also known as the Q or Quiescent Point.

7. r'e

Called R E PRIME, it is the ac resistance of the forward biased base-emitter junction. This ac resistance is approximately equal to 25 mV/I_E in mA.

8. SATURATION REGION

The area of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also, V_{CE} is very low, frequently no more than several tenths of a volt.

9. SWAMPING RESISTOR

See No. 4, Emitter Swamping Resistor.

10. VOLTAGE GAIN

A measure of how much an amplifier stage can increase the input signal level. It is expresssed as:

$$A_v = V_{out} / V_{in}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. The best collector operating point for a CE amplifier is close to:

   a. cut-off.
   b. saturation.
   c. the center of the linear region.
   d. any of the above.

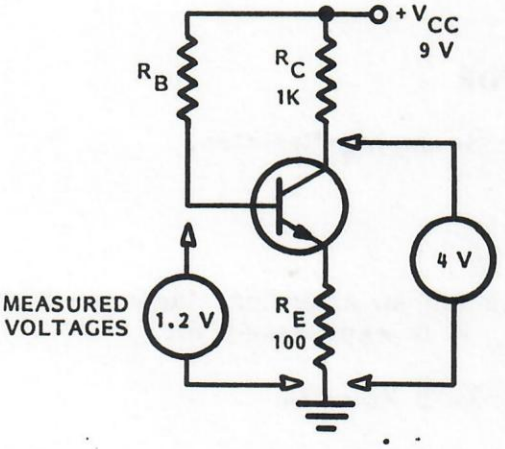


Figure 2 above refers to questions 2 to 9.

2. For the circuit of Figure 2, the voltage drop across R_C is:

   a. 4 volts.
   b. 5 volts.
   c. 9 volts.
   d. insufficient data.

3. For the circuit of Figure 2, the collector current is:

   a. 2 mA.
   b. 4 mA.
   c. 5 mA.
   d. 9 mA.

4. For the circuit of Figure 2, the voltage drop across R_E is:

   a. 0.5 volts.
   b. 5 volts.
   c. 4 volts.
   d. 0.4 volts.

5. For the circuit of Figure 2, the base-emitter voltage is:

   a. 0.5 volts.
   b. 0.7 volts.
   c. 1.2 volts.
   d. 4 volts.

6. For the circuit of Figure 2, the value of r'e is:

   a. 5 ohms.
   b. 25 ohms.
   c. 50 ohms.
   d. 105 ohms.

7. The theoretical voltage gain for the circuit of Figure 2 is:

   a. 200.
   b. 100.
   c. 50.
   d. none of the above.

8. If the beta of the transistor in Figure 2 is 100, the base current flowing through R_B is:

   a. 5 μA.
   b. 50 μA.
   c. 5 mA.
   d. none of the above.

9. If the circuit in Figure 2 has a voltage gain of 90 and the maximum allowable collector voltage swing is 7.5 volts peak-to-peak, the maximum allowable rms input signal is:

   a. 29 mV.
   b. 0.833 volts.
   c. 0.0833 volts.
   d. none of the above.

10. The addition of an emitter swamping resistor to a CE amplifier circuit:

   a. makes changes in r'e ineffectual.
   b. minimizes A_v changes when I_C varies.
   c. minimizes A_v changes when I_E varies.
   d. all of the above.

Biasing Circuits

Lesson No. 5

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 5, Transistor Biasing Stability.

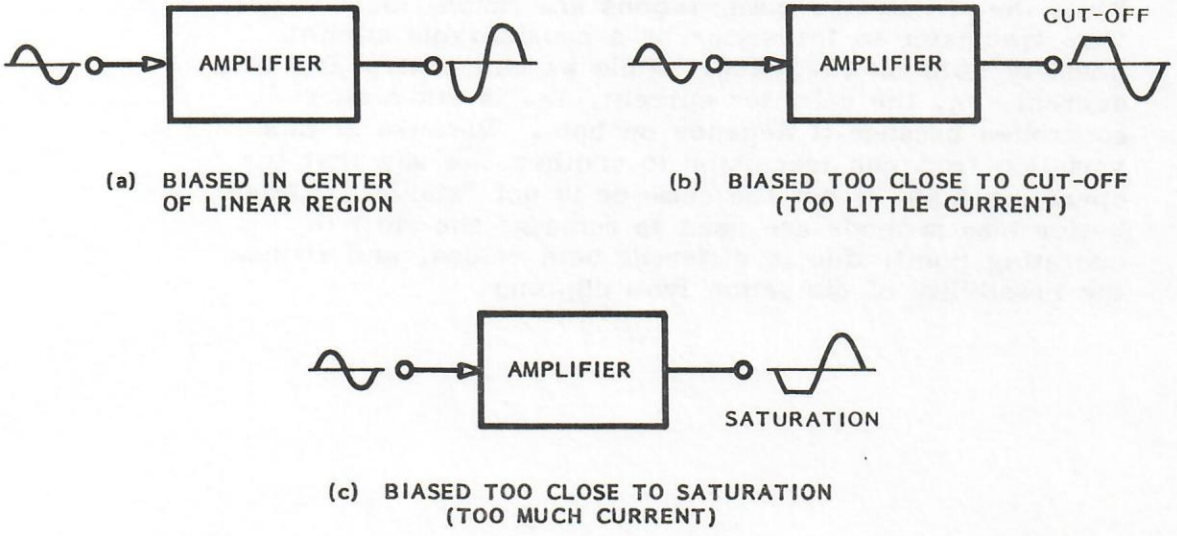
2. The transistor biasing circuits described are:

   a. Base Bias
   b. Collector Feedback Bias
   c. Emitter Bias
   d. Voltage Divider Bias

3. Each of the bias methods is described and compared for stability against changes in transistor beta values.

DISCUSSION

The "biasing" of a transistor in a circuit refers to the adjustment of the dc voltages across the base-emitter junction and the base-collector junction. These voltages are usually chosen to set a dc "operating point" which refers to the setting of the collector current, I_C, and is generally close to the center of the linear operating region. This operating point should result in an amplifier circuit that has no distortion in the output as shown in Figure 1 (a).



(a) BIASED IN CENTER OF LINEAR REGION

(b) BIASED TOO CLOSE TO CUT-OFF (TOO LITTLE CURRENT)

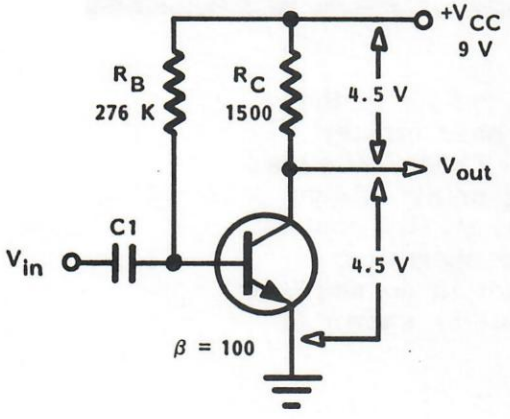
(c) BIASED TOO CLOSE TO SATURATION (TOO MUCH CURRENT)

Figure 1 - Effects of correct and incorrect operating points.

If the operating point is too close to cut-off, the negative half cycle of the input signal can drive the transistor into cut-off resulting in an output with a clipped positive peak as shown in Figure 1(b). An operating point too close to saturation can result in an output with a clipped negative peak as shown in Figure 1(c).

BASE BIAS CIRCUIT

It would seem simple to choose the correct operating point by selecting the required base current to produce an I_C where half of V_{CC} appears across R_C and the other half appears from collector to ground (V_C) as shown in Figure 2.



$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{9 - 0.7}{276 \times 10^3} = \underline{0.03\ \mu A}$$

$$I_C = \beta I_B = 100(0.03) = \underline{3\ mA}$$

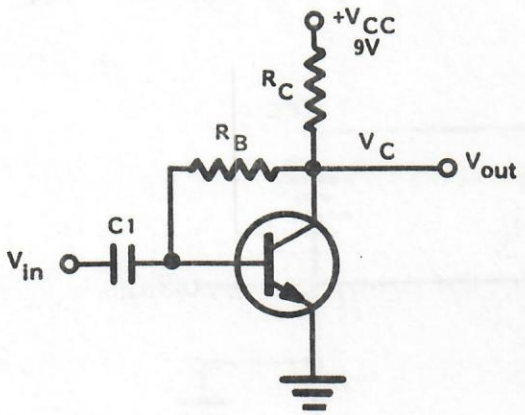
$$V_C = V_{CC} - (I_C R_C) = 9 - (0.003 \times 1500) = \underline{4.5\ V}$$

Figure 2 - Base bias circuit and biasing calculations.

While the circuit and computations are simple, beta varies from transistor to transistor by a considerable amount, possibly between 90 to 400. While we can control the base current, I_B, the collector current, I_C, is not accurately controlled because it depends on beta. Because of this variation from one transistor to another, we say that the operating point is not the same or is not "stable." Other better bias methods are used to minimize the shift in operating point, due to different beta values, and reduce the possibility of distortion from clipping.

COLLECTOR FEEDBACK BIAS

A very good method of biasing a transistor, shown in Figure 3, is called COLLECTOR FEEDBACK bias or VOLTAGE FEEDBACK bias. Observe that the base bias resistor is now connected to the collector rather than V_{CC}.



$V_C = \underline{4.5\ V}$

$V_{BE} = \underline{0.7\ V}$

$I_B = \underline{0.03\ mA}$

$$R_B = \frac{V_C - V_{BE}}{I_B} = \frac{4.5 - 0.7}{0.03 \times 10^{-3}}$$

$R_B = \underline{126.6\ K}$

Figure 3 - Collector feedback bias circuit.

The circuit's name is derived from the fact that the output voltage, V_{out} or V_C at the collector is "fed-back" to the input and it is V_C and R_B that determine the base current, I_B. The resistance of R_B is lower than in the previous base bias circuit because the voltage used to provide the required I_B is V_C rather than V_{CC}. The lower R_B produces the same value of I_B to produce the same output collector voltage, V_C.

Consider the result of an instantaneous increase in beta due to a rise in temperature or from a replacement transistor. The collector current, I_C, increases which results in a decrease in V_C. The lowered V_C lowers I_B which causes I_C to decrease resulting in an increase in V_C. The Collector Feedback Bias circuit is thus self-adjusting. The Collector Feedback Bias circuit corrects the dc operating point for changes in transistor beta and temperature and is a more stable circuit than the earlier Base Bias circuit.

EMITTER BIAS

The EMITTER BIAS circuit uses an emitter resistor, R_E, to set the emitter and collector current rather than using a base resistor, R_B, as in the earlier bias circuits. This circuit is shown in Figure 4, with two power sources, $+V_{CC}$ and $-V_{EE}$.

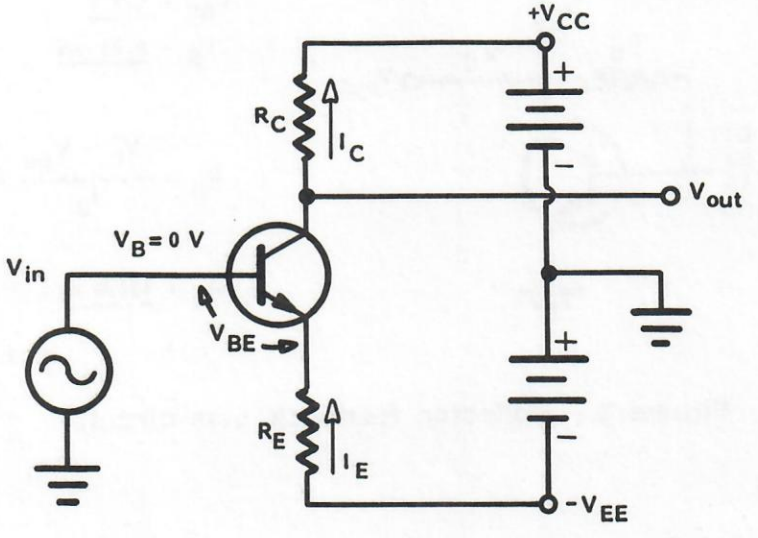


Figure 4 - Emitter bias circuit with two voltage sources.

The base of the transistor in Figure 4 returns to ground through the input generator and the base-emitter junction is forward biased by the negative V_{EE} supply. This results in a drop across R_E equal to $V_{EE} - V_{BE}$. The emitter current, I_E (and thus the collector current, I_C) is now set only by the value of R_E and V_{BE} (both of which are constant and do not vary much) where $I_E = (V_{EE} - V_{BE})/R_E$. This makes I_E independent of beta and, since I_C is approximately equal to I_E, the collector operating point does not vary with temperature, beta or transistor replacement. This specific biasing circuit is not popular because it requires two power supplies, but a variation of this circuit is discussed next as Voltage Divider Biasing. It requires only one power supply and I_C is still determined by the emitter resistor value, R_E.

VOLTAGE DIVIDER BIAS

The VOLTAGE DIVIDER BIAS system is most widely used for amplifier circuits. The circuit requires only a single power supply as shown in Figure 5.

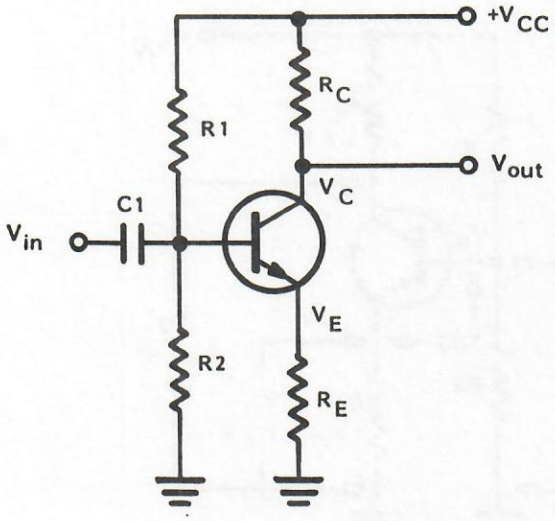


Figure 5 - Voltage divider biased common emitter amplifier circuit.

The circuit of Figure 5 is called voltage divider bias because R1 and R2 form a voltage divider from V_{CC} to ground. The voltage drop across R2 forward biases the base-emitter junction of the transistor while the voltage drop across R1 reverse biases the base-collector junction. The voltage divider circuit is actually the equivalent of the emitter bias circuit with only one power supply.

VOLTAGES IN VOLTAGE DIVIDER BIAS CIRCUIT

The voltage divider bias circuit is drawn again in Figure 6 to show the voltage distribution. Resistors R1 and R2 form a voltage divider across V_{CC}. Because the only current load on the divider is I_B, which is very small, if R1 and R2 are not too large, the divider may be considered "unloaded."

Thus, the voltage at the base, V_B (the drop across R2), is equal to:

$$V_B = V_{R2} = V_{CC} \frac{R2}{R1 + R2}$$

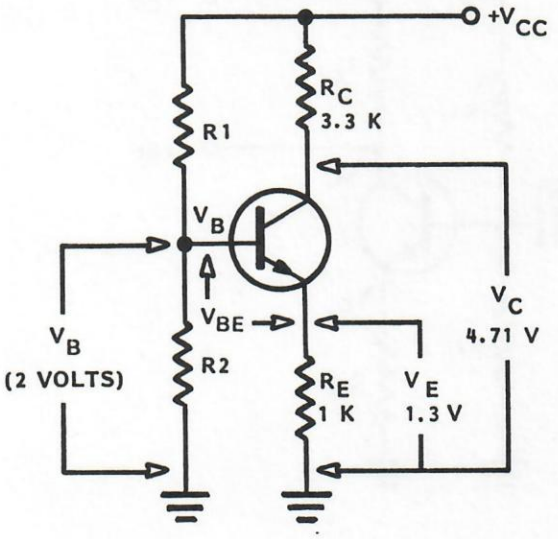


Figure 6 - Common emitter voltage divider bias circuit voltage distribution.

For the circuit of Figure 6, given a voltage drop across R2 of $V_B = 2$ volts and a V_{BE} of 0.7 volts, the emitter voltage, V_E, across R_E is found from:

$$V_E = V_B - V_{BE} = 2 - 0.7 = \underline{1.3\ V}$$

Given that R_E is 1 K, the emitter current and thus the collector current also, is found from:

$$I_E = I_C = V_E/R_E = 1.3/1000 = \underline{1.3\ mA}$$

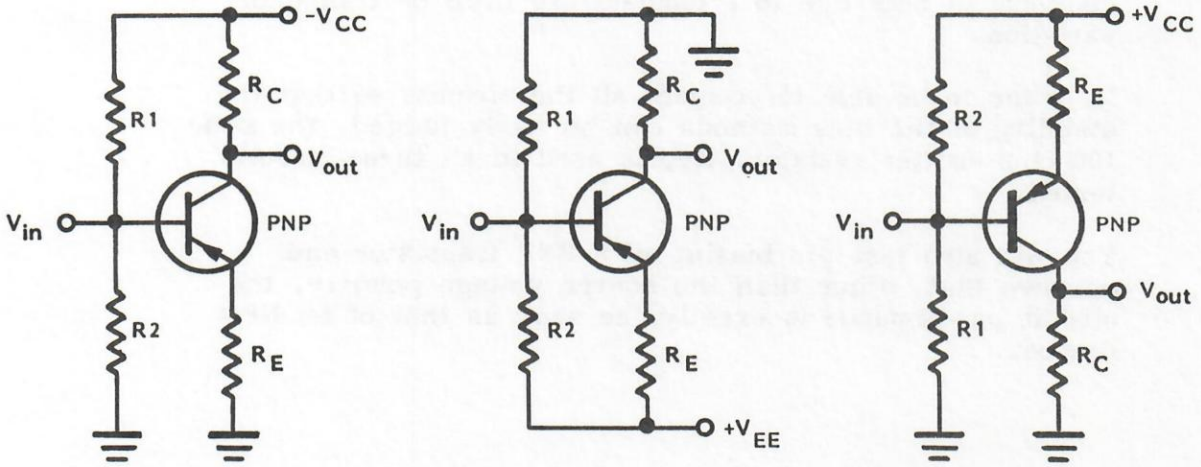
Given that R_C is 3.3 K and V_{CC} is 9 volts, the collector voltage, V_C, is found from:

$$V_C = V_{CC} - (I_C\ R_C) = 9 - (1.3 \times 10^{-3})(3.3 \times 10^{3}) = \underline{4.71\ V}$$

This means that the dc operating point is set by V_{CC}, the voltage divider resistors R1 and R2, the base-emitter voltage drop ($V_{BE} = 0.7$ V) and R_E. It is thus independent of the transistor beta and so is very stable.

PNP TRANSISTOR BIASING

As explained earlier, PNP transistors require bias voltages of the opposite polarity compared to the NPN transistors. A Voltage Divider biased PNP transistor amplifier is shown in Figure 7(a). Notice that the only differences are the PNP transistor (emitter arrow points inward) and the supply voltage ($-V_{CC}$) is NEGATIVE with respect to ground.



(a) PNP WITH $-V_{CC}$ SUPPLY

(b) PNP WITH $+V_{CC}$ SUPPLY

(c) INVERTED TRANSISTOR

Figure 7 - Methods of operating and drawing biased PNP transistors.

When a voltage source that is negative with respect to ground is not available, but a positive voltage source is, the circuit of Figure 7(b) is used.

The one problem found with the drawing in Figure 7(b) is that it is not conventional to draw a circuit with a positive voltage source connected at the bottom and ground at the top. Therefore, the exact same transistor circuit is often drawn "inverted" as in Figure 7(c) and is shown in what is sometimes referred to as the "Upside Down Convention." The circuit in (c) is exactly the same as that shown in (b) except that it is drawn upside down so that V_{CC} is again at the top of the drawing and ground is at the bottom.

EXPERIMENT OVERVIEW

In Experiment No. 5, you will test the bias stability of each circuit; Base Bias, Collector Feedback Bias, and Voltage Divider Bias. In order to simulate a change in transistor beta, we will place a 100K resistor from the transistor base to emitter to "divert" or "shunt" base current around the base-emitter junction. This simulates a decrease in beta due to a temperature drop or transistor variation.

In order to be able to compare all the circuits so that the stability of the bias methods can be fairly judged, the same 100 ohm emitter resistor, R_E, is used in all three circuits tested.

You will also test the biasing of a PNP transistor and observe that, other than the source voltage polarity, the circuit performance is exactly the same as that of an NPN device.

KEY TERMS

1. ACTIVE REGION

   The area of operation of a transistor amplifier where variations in collector current are directly proportional to variations in base current. It is also called the linear region.

2. BASE BIAS

   A method of biasing the base of a transistor by connecting a resistor from V_{CC} to the base terminal. It is the simplest but most unstable of all the bias methods.

3. BETA (β)

   The current gain of a transistor in the CE configuration. It is equal to the ratio of I_C / I_B.

4. COLLECTOR FEEDBACK BIAS

   A method of biasing the base of the transistor by connecting a resistor from the base to the collector. This is a more stable biasing method than simple Base Bias.

5. CUT-OFF

   The region of transistor operation where the base current is zero, resulting in no collector current and thus maximum V_C.

6. DISTORTION

   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is the result of operating in the non-linear regions of an amplifier. It can typically be from clipping due to a poor biasing circuit.

7. EMITTER BIAS

A very stable method of biasing a transistor amplifier that consists of adding a second power source labelled V_{EE}, and a series emitter resistor to set the value of I_E.

8. NEGATIVE FEEDBACK

A voltage fed back from the output of an amplifier to the input of the amplifier with the output thus cancelling a portion of the input signal. The process is also called "NEGATIVE FEEDBACK" or DEGENERATION because it causes a deterioration or lowering of the stage gain. It also improves bias stability.

9. OPERATING POINT

Also called the Quiescent or Q point, it is the value of I_C and V_{CE} with no input signal, when I_C and V_{CE} are "at rest." The operating point is set by the value of the base bias.

10. PNP

A transistor formed in the PNP material sequence. It requires a negative collector and base voltage with respect to the emitter.

11. Q POINT

See No.9, Operating Point, above.

12. SATURATION

The area of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C.

13. STABILITY

The ability of an amplifier to maintain its designed operating point against changes in temperature, beta and transistor replacement.

14. V_{CC}

The voltage source applied to the collector circuit of a transistor amplifier.

15. V_{EE}

The voltage source used to forward bias the emitter-base junction in the transistor. This is applied to the emitter.

16. VOLTAGE DIVIDER BIAS

The most often used bias circuit for amplifiers. Its name is derived from the resistive voltage divider used to set the voltage applied to its base.

ASSIGNMENT

Answer the following multiple choice questions.

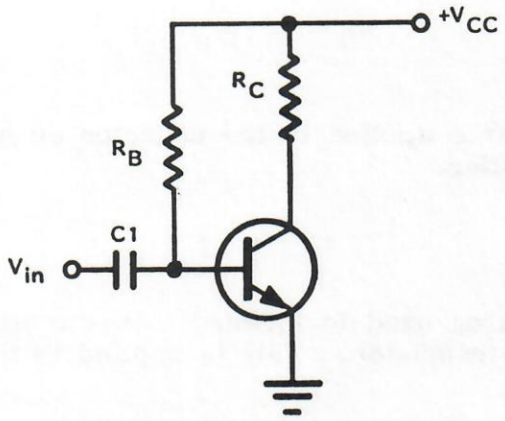


Figure 8 above refers to questions 1 and 2.

1. For the circuit of Figure 8 above, given a V_{CC} of 20 volts and a desired base current of 60 μA, the necessary value of R_B is:

   a. 333.3 K.
   b. 1.66 megohms.
   c. 166 K.
   d. none of the above.

2. For the circuit of Figure 8, given an I_B of 75 μA and a beta of 175, I_C is closest to:

   a. 175 mA.
   b. 175 μA.
   c. 13 mA.
   d. none of the above.

3. The most stable bias configuration is:

   a. base bias.
   b. collector feedback bias.
   c. voltage divider bias.
   d. none of the above.

4. Emitter bias is not used often because it:

   a. requires 2 voltage sources.
   b. is unstable.
   c. is a complex circuit.
   d. all of the above.

5. The voltage divider bias system is used most frequently because it:

   a. is the simplest circuit.
   b. is stable.
   c. requires 2 voltage sources.
   d. all of the above.

Transistor Bias Stability 5

OBJECTIVES

When you finish this experiment you will be able to:

1. Wire and test the stability of the Base Bias circuit.
2. Wire and test the stability of the Collector Feedback Bias circuit.
3. Wire and test the stability of the Voltage Divider Bias circuit.
4. Compare the relative stability of each of the bias systems and explain why the Voltage Divider system is best.
5. Measure the voltage distribution in the Voltage Divider Bias circuit.
6. Wire and test a Voltage Divider Bias amplifier circuit using a PNP transistor.

REFERENCE

CES Lesson J1-5, Biasing Circuits

BACKGROUND

1. The BIASING of a transistor refers to the adjustment of the dc voltages and currents so that the transistor operates in the desired region, in our example the LINEAR REGION.

2. If a transistor circuit is initially biased properly, the biasing may change because BETA changes with temperature variations or when a replacement transistor is used. A stable bias circuit, therefore, independent of beta is desired.

3. The four major biasing methods are: base biasing, collector feedback biasing, emitter biasing, and voltage divider biasing. The latter is the most often used biasing system.

4. This Experiment, No. 5, is in four parts:

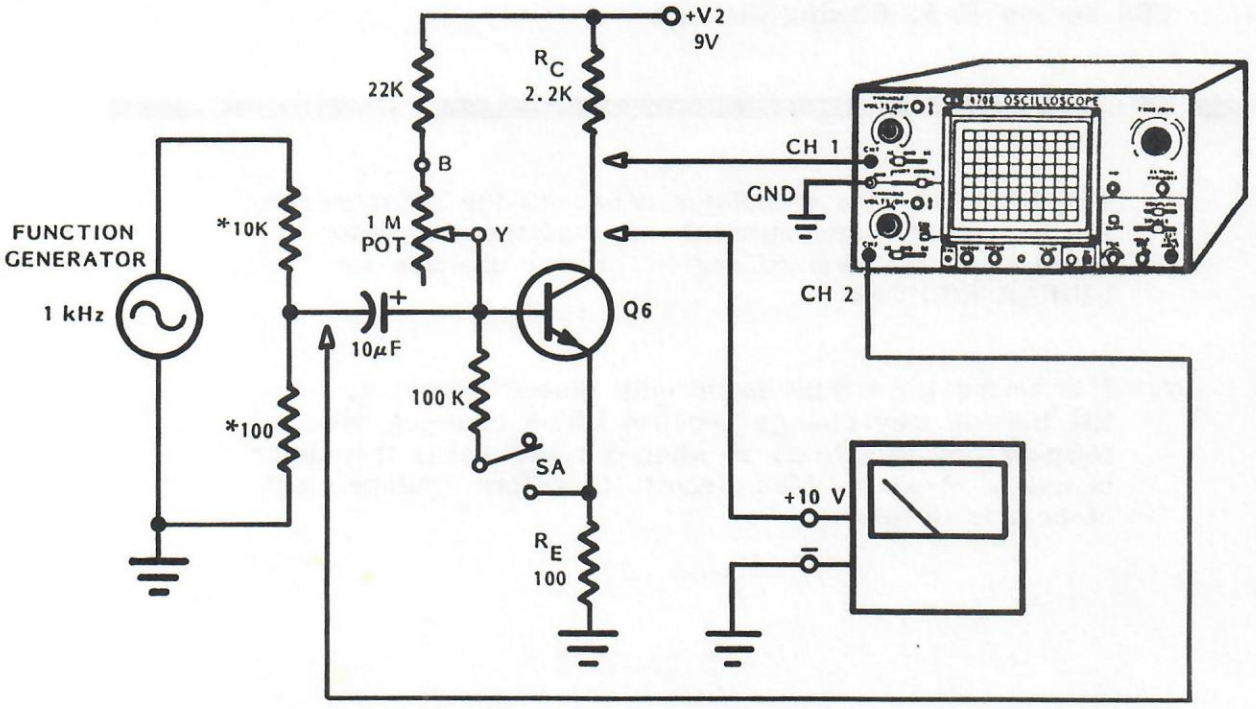
   5.1 Base Biased CE Amplifier
   5.2 Collector Feedback Bias
   5.3 Voltage Divider Bias
   5.4 PNP Transistor Biasing

PROCEDURE

5.1 BASE BIASED CE AMPLIFIER

In the first part of this experiment, we will wire a base biased CE amplifier but with a small emitter resistor. We will then test the abililty of the circuit to maintain its operating point when the transistor performance (beta) is varied. After that, we will check the operating point when changing to another but identical type transistor.

1. Wire the base biased common emitter amplifier circuit shown in Figure 1.



*NOTE: If a HI-LO output switch is on your trainer, omit these two resistors, connect directly to the sine output and place the HI-LO switch to LO.

Figure 1 - Common emitter base bias EXPERIMENT.

The 1 meg pot is used to set the operating point by adjusting I_B. The 100 ohm emitter resistor is used in each of the circuits tested to allow a valid comparison of stability.

2. Set switch SA, in Figure 1, UP to remove the 100 K "Beta Change Resistor" from the circuit.

   Set the Function Generator Sine Ampl. control fully CCW for no ac input signal.

3. Adjust the 1 meg bias pot to achieve a Q point that results in a V_C of 4.5 volts as measured on the Ed-Lab panel dc voltmeter.

4. Set switch SA DOWN to insert the 100 K resistor. This represents a LOWER BETA. Read the new collector voltage and enter the value in Line A, Column 2 of Table 1.

CIRCUIT	1 NORMAL BIAS Q6 V_C	2 LOWER BETA Q6 V_C	3 NEW TRANSISTOR Q7 V_C	4 $V_{out\ ac}$ Q7	5 A_v Q7
(A) BASE BIAS	4.5 V				
(B) COLLECTOR BIAS	4.5 V				
(C) VOLTAGE DIV. BIAS	4.5 V				

TABLE 1 - Amplifier operating points and voltage gains.

The "reduction" in beta causes a shift in operating point from the V_C of 4.5 volts to a higher voltage.

5. Set switch SA UP to remove the 100 K resistor. Change the three wires (C,B,E) from transistor Q6 to transistor Q7.

   Has the Q point shifted because of the change in transistors?

   _____

   Enter the new value of V_C for transistor Q7 in Table 1, Line A, Column 3.

Transistors Q6 and Q7 are identical types. Do you conclude that they have an identical value of beta? _____

GAIN OF BASE BIAS CIRCUIT

6. Using the Q7 circuit now wired, measure the amplifier voltage output with an input of 100 mV p-p (0.1 V) as indicated on the scope. Record the output voltage on Line A, Column 4 of Table 1.

   Calculate and enter the circuit voltage gain, A_v, in Line A, Column 5 of Table 1.

You may conclude from the above that when using the base bias circuit, a change in beta or transistor will cause a shift in the operating point.

5.2 COLLECTOR FEEDBACK BIAS

In this part of the experiment, we will wire and test the collector feedback bias circuit and compare its bias stability and gain to that measured for the base bias circuit tested above. Because of the feedback, we expect the bias stability to be better and the gain to be lower.

7. Move all three transistor connections (C, B, E) back to Q6 from Q7.

   Modify the Q6 circuit by disconnecting the 22 K resistor lead from +V2 and connecting it to the Q6 collector as shown in Figure 2. Otherwise the circuit is the same.

8. Reduce the ac input signal to zero and, with SA UP, adjust the 1 meg bias pot for a V_C of 4.5 volts as read on the panel meter.

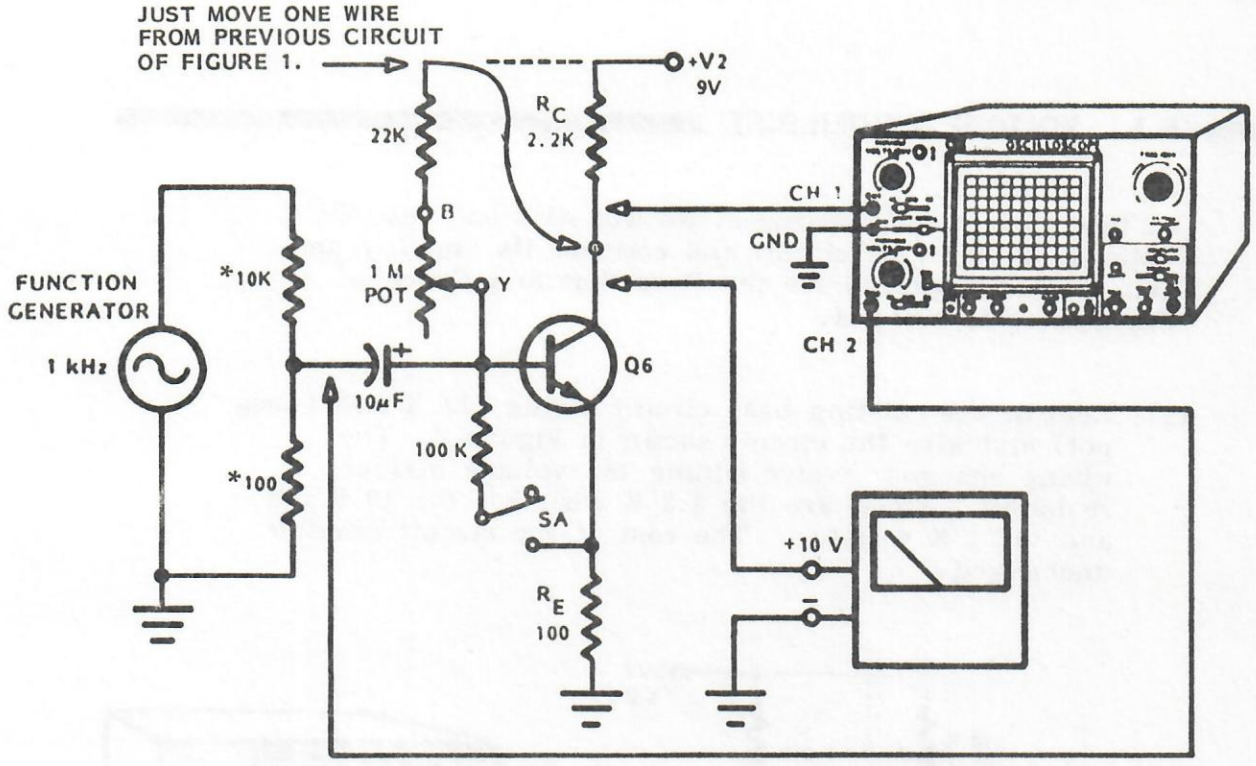
9. Set SA DOWN to place the 100K resistor in the circuit simulating a change in beta. Read the new value of V_C on the meter and record it in Table 1, Line B, Column 2.

   How does the shift in the V_C operating point for this circuit compare to the V_C shift in the base bias circuit (step 4)?

   _____

   _____

   _____



*NOTE: Not used if trainer has HI-LO switch. Set switch at LO.

Figure 2 - Common emitter collector feedback EXPERIMENT.

10. Switch the 100 K resistor out of the circuit (SA UP) and substitute Q7 in place of Q6. Record the new value of V_C in Table 1, Line B, Column 4.

    How does the change in operating point between transistors Q6 and Q7, with Collector Feedback Bias, compare to the change with the simple Base Bias circuit? _____

    _____

    _____

11. Using Q7, (with SA UP so the 100K resistor is out of the circuit) repeat the gain test using an input of 100 mV (0.1 V) p-p. Record the output voltage and the calculated stage gain on line B of Table 1. The gain for this circuit is normally slightly lower than that of the Base Bias circuit because some of the inverted output from the collector is fed back to the input and, being 180° out of phase, cancels a small part of the input signal.

    Is the gain in The Collector Feedback Bias circuit lower than the gain in the Base Bias circuit?

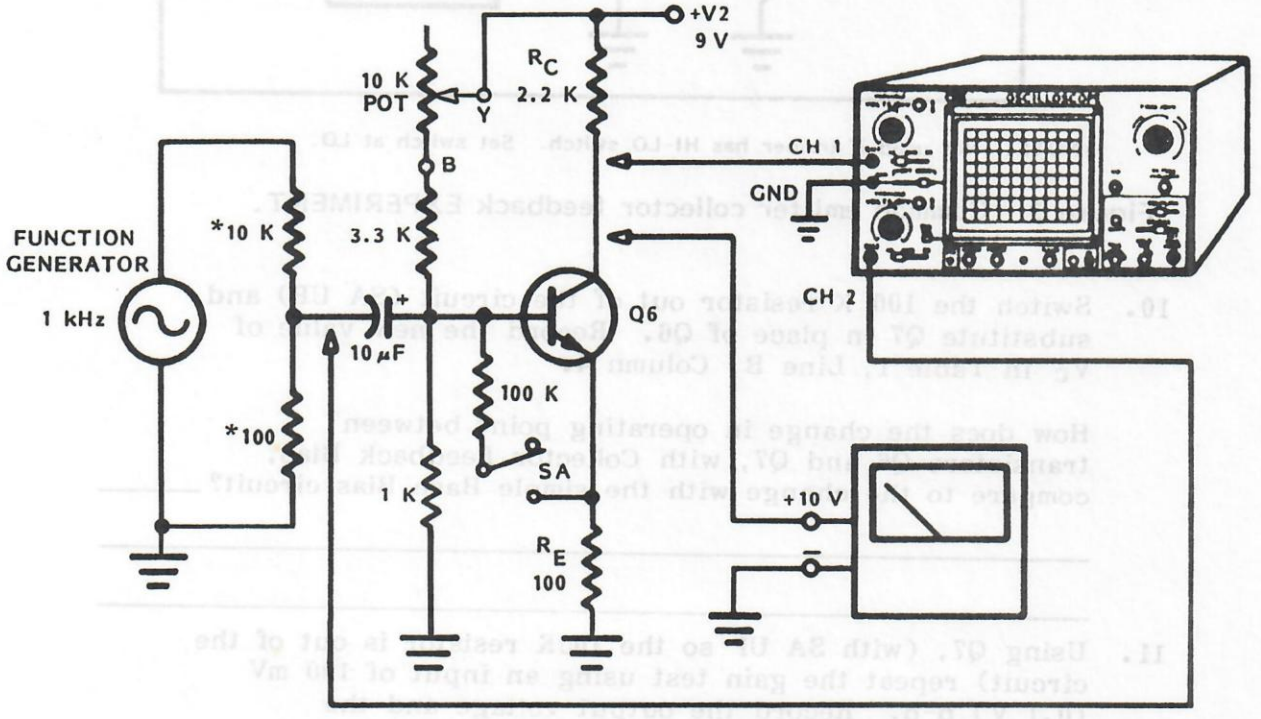
    _____

You may conclude from the above that Collector Feedback bias is more stable than the Base Bias circuit. Also, the voltage gain of this circuit is slightly reduced.

5.3 VOLTAGE DIVIDER BIAS

In this part of the experiment we will wire and test the Voltage Divider Bias circuit and compare its stability and gain to that measured for the Base Bias and Collector Feedback Bias circuits.

12. Remove the existing base circuit wiring (22 K and 1 meg pot) and wire the circuit shown in Figure 3. The wiring changes involve adding the voltage divider resistors. These are the 3.3 K resistor, the 10 K pot and the 1 K resistor. The rest of the circuit remains unchanged.



*NOTE: Not used if trainer has HI-LO switch. Set switch at LO.

Figure 3 - Common emitter voltage divider bias EXPERIMENT.

13. Set switch SA UP (100 K base-emitter resistor out) and set the ac input level to zero. Adjust the 10 K bias pot for a V_C of 4.5 volts.

14. Switch the 100 K bias shift resistor into the circuit. Read the new bias value of V_C and record it in Table 1, Line C, Column 2.

    How much does V_C shift with this bias circuit compared to the other bias circuits?

    _____

    _____

    _____

15. Switch the 100 K resistor out of the circuit (SA UP) and change from transistor Q6 to Q7.

    Measure and record the V_C bias value for transistor Q7 in Line C, Column 3 of Table 1.

    Is the operating point, using Q7, any different than that of Q6?

    _____

    _____

    This indicates that the difference in beta between Q6 and Q7 has not affected the operating point when a Voltage Divider Bias circuit is used.

16. Using the Q7 circuit with SA UP (no 100 K) determine the gain by measuring the amplifier output voltage using an ac input signal of 0.1 V. Record the output level and the stage gain in Table 1, Line D.

You can conclude from examination of the data collected in Table 1 that each of the bias circuits used were progressively more stable and that the Voltage Divider Bias circuit gave the best results.

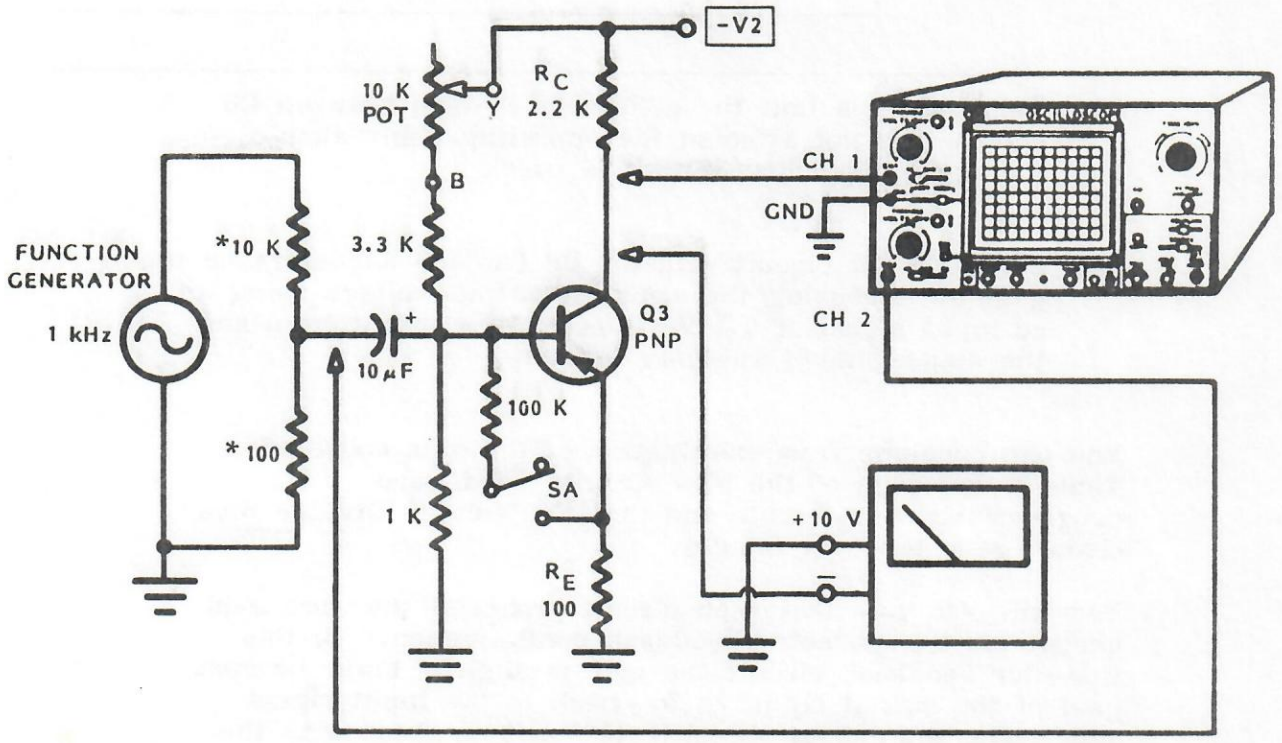
You will also note that each circuit produced the same gain except for the Collector Feedback configuration. In this Collector Feedback circuit the gain is slightly lower because part of the output signal is fed back to the input signal and, since the output signal is 180° out of phase with the input signal, part of the input signal is cancelled. This feedback is called DEGENERATION, INVERSE FEEDBACK OR NEGATIVE FEEDBACK.

5.4 PNP TRANSISTOR BIASING

In this part of the experiment you will transfer the circuit connections from the NPN transistor to a similar PNP transistor. You will make the necessary changes in the power source to operate the circuit and then compare the circuit performance to that of the NPN transistor.

17. Turn off the trainer power. Move the three transistor leads from Q7 (NPN) to Q3, a PNP transistor. The circuit is the same as before but the following two changes are necessary before operation is possible.

    Reverse the voltmeter polarity by changing the +10 and -10 wires connected to the meter. Move all V_{CC} leads from +V2 to -V2 as shown in Figure 4. Otherwise the circuit is the same as before.



* NOTE: Not used if trainer has HI-LO switch. Set switch at LO.

Figure 4 - Common emitter PNP bias EXPERIMENT.

18. With SA UP and no input signal, apply power and adjust the 10 K pot for a V_C bias of 4.5 volts.

19. Set the ac input signal level to 0.1 volts p-p. Measure the output signal voltage and record it below.

PNP AMPLIFIER	V_{out} = Vp-p

20. Calculate the amplifier voltage gain and record it below.

PNP AMPLIFIER	A_v =

Compare the gain developed by Q3, the PNP transistor, to that developed by Q7, the NPN transistor, in the voltage divider configuration from Table 1. Is there any significant difference? _____

You may conclude from the above that, in this circuit, other than a reversal of polarity of the voltage source, the PNP transistor amplifier performs no differently than the NPN amplifier.

CONCLUSIONS

We have learned from this experiment that:

1. The Base Biased amplifier circuit has the most unstable operating point of all the biasing methods.

2. The Base Biased circuit operating point varies with temperature changes and changes in transistor beta value.

3. When the operating point moves too far from the center of the linear region of the transistor, the output signal may be distorted.

4. The Collector Feedback Bias circuit provides a partial compensation for shifts in operating point by moving the operating point back towards normal, automatically.

5. Voltage divider bias is a more stable circuit than either Base Bias or Collector Feedback bias.

6. Voltage divider bias is the same as Emitter Bias except that it uses a voltage divider in the base circuit to provide the required voltages rather than two power supplies.

7. A PNP transistor may be used with any of the bias circuits. It is necessary only to reverse the polarities of the source voltages.

KEY TERMS

1. ACTIVE REGION

The area of operation of a transistor amplifier where variations in collector current are directly proportional to variations in base current. It is also called the linear region.

2. BASE BIAS

A method of biasing the base of a transistor by connecting a resistor from V_{CC} to the base terminal. It is the simplest but most unstable of all the bias methods.

3. BETA (β)

The current gain of a transistor in the CE configuration. It is equal to the ratio of I_C / I_B.

4. COLLECTOR FEEDBACK BIAS

A method of biasing the base of the transistor by connecting a resistor from the base to the collector. This is a more stable biasing method than simple Base Bias.

5. CUT-OFF

The region of transistor operation where the base current is zero, resulting in no collector current and thus maximum V_C.

6. DEGENERATION

A loss or deterioration of a function such as amplifier gain. Often deliberately introduced in the form of Negative Feedback, defined in No. 9 below, and can be accomplished by an unbypassed emitter resistor or a collector feedback resistor.

7. DISTORTION

An undesired change in the output signal waveshape as compared to the input signal waveshape. It is the result of operating in the non-linear regions of an amplifier. It can typically be from clipping due to a poor biasing circuit.

8. EMITTER BIAS

A very stable method of biasing a transistor amplifier that consists of adding a second power source, labelled V_{EE}, and a series emitter resistor to set the value of I_E.

9. NEGATIVE FEEDBACK

A voltage fed back from the output of an amplifier to the input of the amplifier with the output thus cancelling a portion of the input signal. The process is also called "NEGATIVE FEEDBACK" or DEGENERATION because it causes a deterioration or lowering of the stage gain. It also improves bias stability.

10. OPERATING POINT

Also called the Quiescent or Q point, it is the value of I_C and V_{CE} with no input signal, when I_C and V_{CE} are "at rest." The operating point is set by the value of the base bias.

11. PNP

A transistor formed in the PNP material sequence. It requires a negative collector and base voltage with respect to the emitter.

12. Q POINT

See No. 10, Operating Point, above.

13. SATURATION

The area of transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C.

14. STABILITY

The ability of an amplifier to maintain its designed operating point against changes in temperature, beta and transistor replacement.

15. V_{CC}

The voltage source applied to the collector circuit of a transistor amplifier.

16. V_{EE}

The voltage source used to forward bias the emitter-base junction in the transistor. This is applied to the emitter.

17. VOLTAGE DIVIDER BIAS

The most often used bias circuit for amplifiers. Its name is derived from the resistive voltage divider used to set the voltage applied to its base.

ASSIGNMENT

Answer the following multiple choice questions.

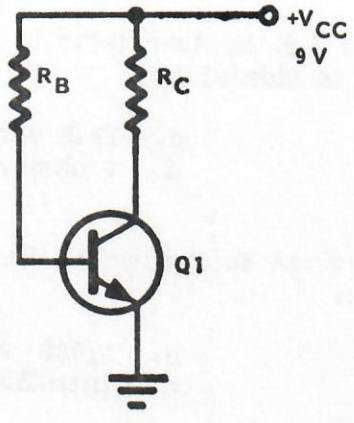


Figure 5 above refers to questions 1 to 7.

1. The circuit of Figure 5 uses:

   a. Base Bias.
   b. Collector Feedback Bias.
   c. Emitter Bias.
   d. Voltage Divider Bias.

2. The circuit of Figure 5 is the most:

   a. unstable of all the bias methods.
   b. stable bias system.
   c. often used circuit.
   d. none of the above.

3. For the circuit of Figure 5, given that Q1 is silicon and the base current is 50 microamperes, the value of R_B will be closest to:

   a. 185 K.
   b. 166 K.
   c. 1.8 M.
   d. 1.7 M.

4. Given a base current of 50 μA and a beta of 110 for the circuit of Figure 5, I_C is closest to:

   a. 160 mA.
   b. 110 mA.
   c. 5.5 mA.
   d. 2.2 mA.

5. The value of r'e for the transistor in Figure 5, given an I_E of 2 mA, is closest to:

   a. 25 ohms.
   b. 20 ohms.
   c. 12.5 ohms.
   d. 2 ohms.

6. Given an I_C of 2 mA in Figure 5, the most desirable value for R_C is:

   a. 4500 ohms.
   b. 2250 ohms.
   c. 1,000 ohms.
   d. Insufficient data to compute.

7. The approximate gain of the amplifier shown in Figure 5, given an R_C of 2.2 K and and I_C of 2 mA, is:

   a. 176.
   b. 1100.
   c. 88.
   d. none of the above.

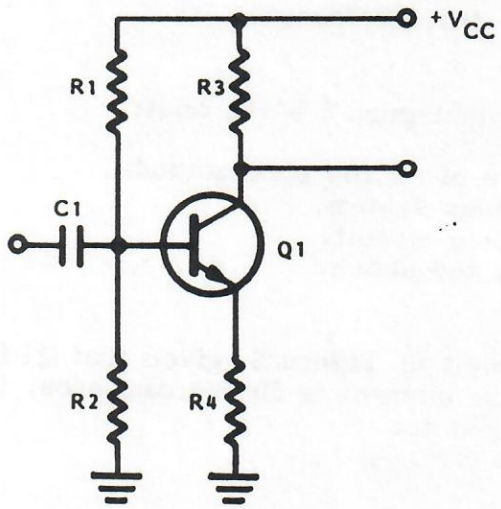


Figure 6 above refers to questions 8 to 11.

8. The circuit of Figure 6 uses:

   a. Base Bias.
   b. Collector Feedback Bias.
   c. Emitter Bias.
   d. Voltage Divider Bias.

9. The circuit of Figure 6 is the most:

   a. unstable of all the bias methods.
   b. stable bias system.
   c. rarely used.
   d. none of the above.

10. For the circuit of Figure 6, given that Q1 is silicon and the voltage drop across R4 is 1 volt, the voltage drop across R2 is:

   a. 0.3 V.
   b. 0 V.
   c. 1.7 V.
   d. 3.4 V.

11. Given that Q1 in Figure 6 is replaced by a transistor that has a higher beta, the:

   a. stage gain will increase.
   b. stage gain will decrease.
   c. voltage drop across R1 will increase.
   d. none of the above.

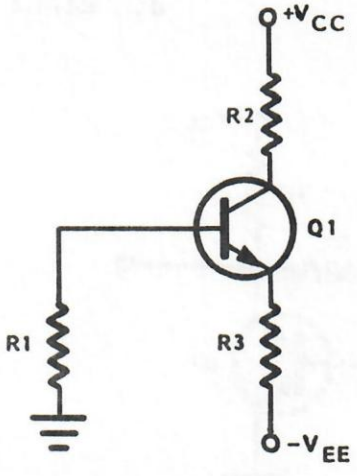


Figure 7 above refers to questions 12 to 16.

12. The circuit of Figure 7 uses:

a. Base Bias.
b. Collector Feedback Bias.
c. Emitter Bias.
d. Voltage Divider Bias.

13. The emitter current in Figure 7 is set by:

a. $V_{CC} - V_{CE} / R1$.
b. $V_{EE} + V_{CE} \times R1$.
c. $V_{CC} - V_{BE} / R2$.
d. $V_{EE} - V_{BE} / R3$.

14. The circuit of Figure 7 is:

a. as stable as the circuit of Figure 6.
b. the least stable of all the bias methods.
c. the most frequently used bias method.
d. none of the above.

15. In the circuit of Figure 7, the normal voltage from the base to ground, V_{R1}, is approximately equal to:

a. V_{BE}.
b. V_{CC}.
c. zero volts.
d. none of the above.

16. The voltage gain for the circuit shown in Figure 7 is determined from:

a. R2/R1
b. R2/R3
c. R3/R2
d. R1/R2

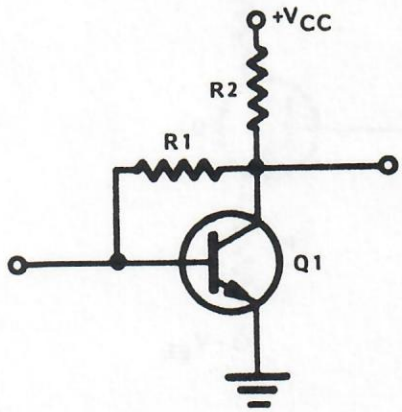


Figure 8 above refers to questions 17 to 20.

17. The circuit of Figure 8 employs:

a. Base Bias.
b. Collector Feedback Bias.
c. Emitter Bias.
d. Voltage Divider Bias.

18. The base current in the circuit of Figure 8 is equal to:

a. $(V_{CC} - V_{R2} - V_{BE})/R1$
b. $(V_{CC} - V_{BE} - V_{R2})/R2$
c. $R2/R1 + r'e$
d. none of the above.

19. The voltage gain for the circuit shown in Figure 8 is approximately equal to:

a. $R2/R1$
b. $R2 + R1/r'e$
c. $R2 - R1/r'e$
d. $R2/r'e$

20. If, in the circuit of Figure 8, $+V_{CC}$ is changed to $-V_{CC}$, it is necessary to:

a. add a $+V_{EE}$ source to compensate.
b. change Q1 to an NPN transistor.
c. change Q1 to a PNP transistor.
d. none of the above.

Voltage-Divider Bias Design

Lesson No. 6

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 6, Voltage Divider Biased Amplifier Operation.

2. A common emitter voltage divider biased amplifier is designed. The circuit component values are determined using Ohm's and Kirchhoff's laws. Also, certain basic approximations or design guides called "rules of the thumb" are used.

3. The emitter resistance is divided into two separate resistors, one bypassed with a capacitor as an emitter bias resistor, the other unbypassed to reduce and stabilize the gain.

DISCUSSION

The biasing circuit found to be the most stable in Experiment 5, was the Voltage Divider Bias. For this reason, the voltage divider bias circuit is the most frequently used. This bias method is also referred to as the UNIVERSAL BIAS CIRCUIT, both because it is used in so many circuits and because this same bias circuit can be used in the Common Collector and Common Base configurations as well.

A practical amplifier circuit is different from that used in the biasing experiment (No. 5) and includes the following:

(a) The voltage divider bias resistors are fixed and cannot be adjusted. The adjustment is not needed because the design values provide the proper collector current and the circuit is stable.

(b) Two emitter resistors are used. One, R_D, provides the swamping or degeneration to reduce the ac gain and the other, R_E, the larger resistor, is part of the stable dc bias circuit.

(c) The larger bias resistor, R_E, used for bias stability, has a parallel capacitor so that the resistor affects the dc bias but has a low impedance (through the capacitor) to the ac input signal. Thus, the ac gain is not reduced by the large value emitter resistor. The capacitor is called an AC EMITTER BYPASS CAPACITOR.

(d) The input signal is applied to the base through a series capacitor called the AC INPUT COUPLING CAPACITOR. This capacitor, as used in previous experiments, prevents the input source dc path from affecting the dc base bias voltage.

In this lesson we will "design" a Voltage Divider Biased amplifier with a swamping resistor. The "design" of the amplifier circuit requires the use of Kirchhoff's Law and Ohm's Law, both of which are now very familiar. After calculating the resistance values needed, the amplifier circuit will be wired and tested in Experiment No. 6 and the results compared to the design data.

DESIGN PROCEDURE

In order to calculate the resistance values for the circuit of Figure 1, several "approximations" and guidelines are used. These approximations, for design purposes, are often referred to as "rules of the thumb."

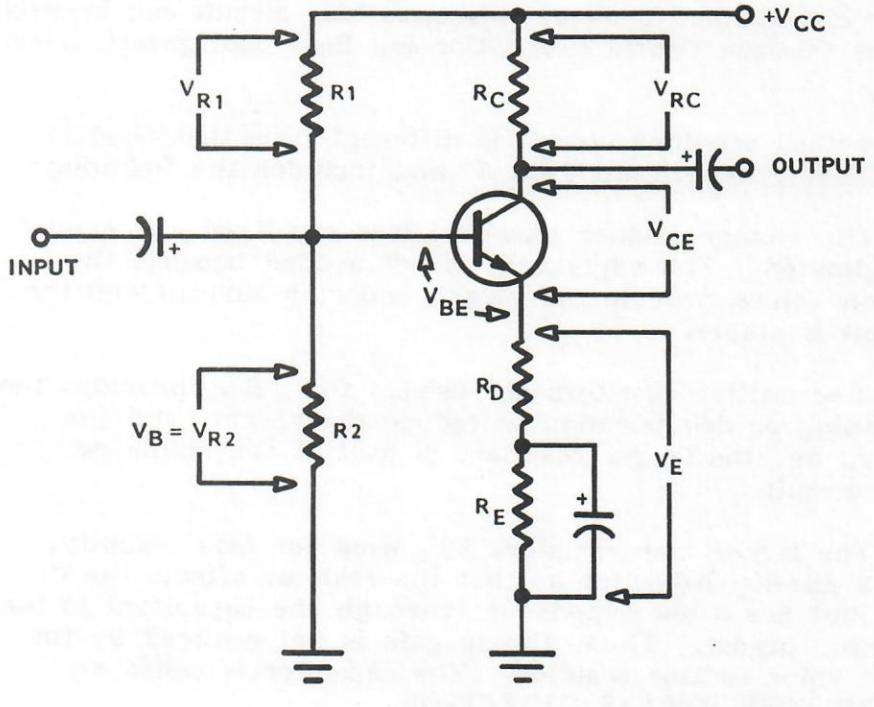


Figure 1 - Voltage distribution in the CE voltage divider bias circuit.

The rules of thumb used when designing the amplifier of Figure 1 are as follows:

1. Make V_E approximately 1/10 of V_{CC} . This leaves 9/10 of V_{CC} to appear across R_C and the collector-to-emitter to provide sufficient voltage for the ac output signal to vary or "swing."

2. The above rule requires that V_{R2} , the base to ground voltage (V_B), equal 1/10 V_{CC} plus V_{BE} .

3. Make R2 equal to 10 R_E so that the voltage divider current will be high enough to be unaffected by the relatively low base current, I_B . It will be shown in the next experiment that the base input resistance is beta times R_E so that R2 is lower than the transistor input resistance. Another way to state this is that the voltage divider resistor values are selected so that the transistor base current will not load the divider and thus will not change the base voltage.

4. Make V_{RC} equal to half of the remaining V_{CC} to allow for maximum undistorted output ac output voltage swing.

$$V_{RC} = \frac{(V_{CC} - V_E)}{2}$$

5. For a small ac signal voltage amplifier with low output power, I_C should be low and can be approximately 1 mA. For higher power outputs, I_C would be higher.

Following the above approximations, it is now possible to determine the component values for the circuit of Figure 1.

A. CALCULATING R_E VALUE

Because V_{CC} is 9 volts, V_{RE} is selected to be:

$$V_{RE} = \frac{1}{10} V_{CC}$$

$$= \frac{1}{10} (9)$$

$$V_{RE} = \underline{0.9 \text{ Volts}}$$

Using the estimated I_E (and thus also I_C) of 1 mA, the value of R_E is found using Ohm's Law.

$$R_E = \frac{V_{RE}}{I_E} = \frac{0.9}{1 \times 10^{-3}}$$

$$R_E = \underline{900 \text{ ohms}}$$

We select a standard value close to 900 ohms. Because this design approach is an approximation, a standard value 1 K resistor will be used for R_E. Thus:

DESIGN VALUE	R_E = 1000 ohms

B. CALCULATING R_C VALUE

The value of R_C will be selected so that it will drop one half of the remaining voltage of V_{CC}. Recall that 1 volt (V_{RE}) of the 9 volts has been used. Thus:

$$V_{RC} = \frac{(V_{CC} - V_{RE})}{2} = \frac{(9)-(1)}{2}$$

$$V_{RC} = \underline{4 \text{ Volts}}$$

The value of R_D will be small and so has been neglected. With V_{RC} as above, and I_C as 1 mA, R_C is determined from:

$$R_C = \frac{V_{RC}}{I_C} = \frac{4}{1 \times 10^{-3}}$$

$$R_C = \underline{4000 \text{ ohms}}$$

We could use a combination of resistors in series or parallel to obtain the 4 K value. We will, however, select a standard 3.3 K resistor as a reasonable value.

DESIGN VALUE	R_C = 3,300 ohms

C. CALCULATING R_D VALUE

Resistor R_D is so called because it introduces DEGENERATION into the circuit. In some texts it is called R_{E1} while R_E is called R_{E2}. In other texts R_D may be defined as r_E where a small letter indicates it to be an ac component and E indicates it to be a dc resistor in the emitter circuit. R_D affects the dc bias only slightly because its value is usually small and it affects the ac voltage gain greatly because, while the R_D value is low, it is much greater than r'e, the internal base-emitter transistor resistance as was demonstrated in the earlier experiments on emitter degeneration and swamping.

The value of the unbypassed resistor, R_D, depends upon the desired gain for the transistor amplifier. Recall that r'e is:

$$r'e = \frac{25}{I_E \text{ (mA)}} = \frac{25}{1} = \underline{25 \text{ ohms}}$$

We will choose a value of 100 ohms for R_D and so the circuit gain is given by:

$$A_v = \frac{R_C}{r'e + R_D} = \frac{3300}{25 + 100}$$

DESIGN GAIN	$A_v = 26.4$

D. CALCULATING V_B VALUE

With $I_E = I_C = 1$ mA, the emitter voltage, V_E, is:

$$V_E = I_E (R_E + R_D)$$

$$= 0.001 (1000 + 100)$$

$$V_E = \underline{1.1 \text{ volts}}$$

The base voltage, measured across R2, is greater than V_E by the base-to-emitter voltage drop. Because a silicon transistor (with a V_{BE} of 0.7 volts) is to be used, V_B is:

$$V_B = V_E + V_{BE} = 1.1 + 0.7$$

$$V_B = \underline{1.8 \text{ volts}}$$

E. CALCULATING THE R1 AND R2 VALUES

The resistance of R2, using the approximation described in step 3 before, is selected as approximately 10 times that of $R_E + R_D$. Thus:

$$R2 = 10\ (R_E + R_D)$$

$$= 10\ (1{,}000 + 100)$$

$$R2 = \underline{11{,}000 \text{ ohms}}$$

We will select the next highest value available.

DESIGN VALUE	R2 = 15,000 ohms

If the R1 and R2 voltage divider resistance values are set low enough so that I_{R1} and I_{R2} are much greater than I_B, then I_{R1} will approximately equal I_{R2}. The value of I_{R2} may be determined from:

$$I_{R2} = \frac{V_B}{R2}$$

Using the V_{BE}, for a silicon transistor, of 0.7 volts:

$$I_{R1} = I_{R2} = \frac{0.7 + 1.1}{15{,}000} = \frac{1.8}{15{,}000}$$

$$I_{R1} = I_{R2} = \underline{0.12 \text{ mA}}$$

The voltage drop across R1 is equal to:

$$V_{R1} = V_{CC} - V_B$$

$$= 9 - 1.8$$

$$V_{R1} = \underline{7.2 \text{ Volts}}$$

Thus, the value of R1 is found from:

$$R1 = \frac{V_{R1}}{I_{R1}} = \frac{7.2}{0.12 \times 10^{-3}}$$

$$R1 = \underline{60{,}000 \text{ ohms}}$$

We will select the 56 K resistance which is available. In general, calculations will not result in available resistance values and design value selections are flexible. The exact measured values will then differ slightly from the design values.

DESIGN VALUE	R1 = 56,000 ohms

The resulting component values from the design procedure are shown in Figure 2. The emitter capacitor value will be made large enough to bypass any ac signal and can be 10 μF. A discussion on how to select the values of C_E and C_C is given in a later experiment on Amplifier Frequency Response.

The diagram in Figure 2 also shows the expected voltages of interest and the expected design gain. If we had wanted a higher gain, we would have selected a higher value of R_C.

The input and output capacitors, C_{C1} and C_{C2}, are used to provide dc isolation so that bias voltage values are not affected by any input or output circuits. The values of the capacitors are normally large (5 μF and 10 μF are used here) to provide good low frequency response as explained later in Unit J2.

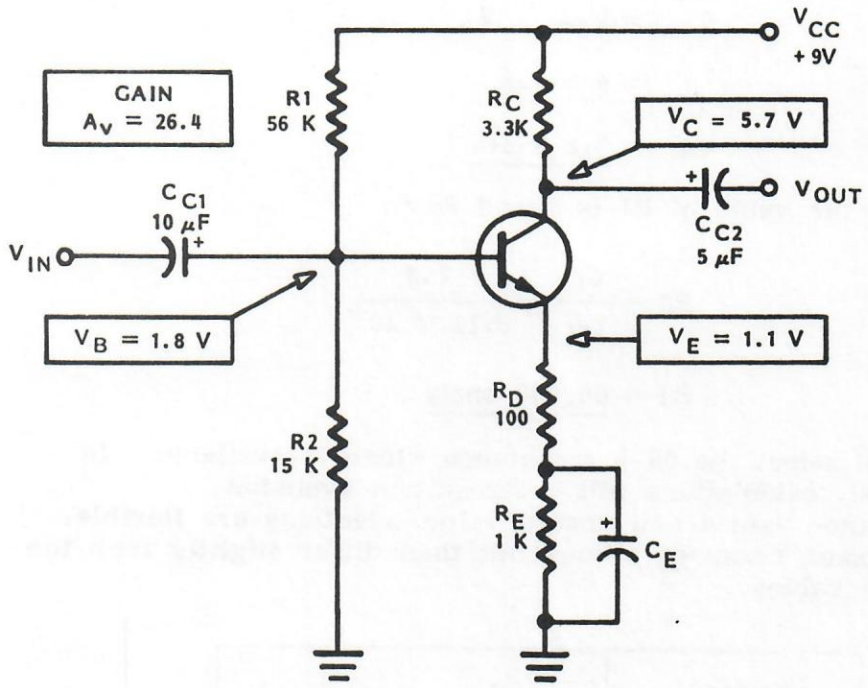


Figure 2 - Calculated component and voltage values for the CE voltage divider bias circuit.

KEY TERMS

1. BETA (β)

   The current gain of a transistor in the CE configuration. It is equal to the ratio of I_C / I_B.

2. CUT-OFF REGION

   The area of transistor operation where the base current is zero, resulting in no collector current and thus maximum V_{CC}.

3. DEGENERATION

   A loss or deterioration of a function such as amplifier gain. Often deliberately introduced into a circuit in the form of an unbypassed emitter resistor to result in stability and a desired lower gain.

4. DISTORTION

   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is the result of operating in the non-linear areas of the amplifier stage.

5. EMITTER BYPASS CAPACITOR

   A capacitor connected in parallel with the emitter resistor or a portion of the total emitter resistance to remove it from the ac input circuit. This bypass capacitor prevents the resistor from causing degeneration.

6. OPERATING POINT

   Also called the Q point, it is the value of I_C and V_{CE} with no input signal, when I_C and V_{CE} are "at rest." The operating point is set by the value of I_B.

7. OVERDRIVE

   Excessive input signal to the amplifier which drives the output signal into saturation or cut-off or both.

8. r'e

Called R E PRIME, it is the ac resistance of the forward biased base-emitter junction. This ac resistance is approximately equal to $25mV/I_E$ in mA.

9. SATURATION REGION

The region of the transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also, V_{CE} is very low, no more than several tenths of a volt.

10. STABILITY

The ability of an amplifier to maintain its design operating point against changes in temperature and different transistors.

11. SWAMPING RESISTOR

A resistor placed in series with the emitter, that is usually 10 times greater in value than r'e. It minimizes the effect on A_v for any change in r'e and also reduces the gain which is often desired.

12. VOLTAGE DIVIDER BIAS

The most often used bias circuit for linear amplifiers. Its name is derived from the resistive voltage divider used to set the base-to-ground voltage.

ASSIGNMENT

Answer the following multiple choice questions.

1. The most stable biasing system for the CE amplifier configuration is the:

   a. voltage divider bias circuit.
   b. base bias circuit.
   c. collector feedback bias circuit.
   d. reverse bias circuit.

2. When two resistors in series are placed in the emitter circuit and one of them is bypassed with a capacitor, the:

   a. bypassed resistor acts as the swamping resistor.
   b. unbypassed resistor acts as the swamping resistor.
   c. bypassed resistor is not part of the dc biasing circuit.
   d. none of the above.

3. In a small signal CE amplifier, the emitter current is often set at approximately:

   a. 0.001 mA.
   b. 1 mA.
   c. 10 mA.
   d. 50 mA.

4. When calculating the component values of a CE amplifier circuit, the emitter voltage is made approximately equal to:

   a. V_{CC}
   b. V_{BE}
   c. V_{CC} /10
   d. V_{CC} (10)

5. The value of the emitter resistance, R_E, for any CE amplifier may be determined from:

   a. V_E / I_C
   b. V_E / I_B
   c. $V_B / I_B + I_C$
   d. $V_B - E / I_C$

Voltage-Divider Biased Amplifier Operation 6

OBJECTIVES

When you finish this experiment you will be able to:

1. Measure the voltages in a voltage divider biased amplifier and compare the measured values to the expected or design values.
2. Wire and test an amplifier with both swamping and bypassed emitter resistors.
3. Observe the effects on the gain of the amplifier with the emitter bypass capacitor removed.
4. Explain the causes of distortion of the output signal when the amplifier is overdriven.
5. Observe the effect on the output signal when the operating point is changed.
6. Observe the effects of faults on circuit voltages and output signal waveforms.

ADDITIONAL EQUIPMENT REQUIRED

Digital Multimeter (Optional)

REFERENCE

CES Lesson J1-6, Voltage Divider Bias Design

BACKGROUND

1. A practical voltage divider biased amplifier circuit can be designed, based on certain approximations and rules of the thumb, using Ohm's and Kirchhoff's laws as was done in the lesson referenced above.
2. The emitter resistor may be divided into two parts, one unbypassed to swamp r'e and to reduce and stabilize the gain, and the other, bypassed with a capacitor so that it does not affect the ac circuit but stabilizes the dc bias circuit.

3. All the resistors required for a CE voltage divider biased amplifier were calculated in Lesson J1-6 and are used to assemble the circuit. Voltage measurements are made in the test circuit and the results are compared to the design data from Lesson J1-6.

4. This experiment is in four parts:

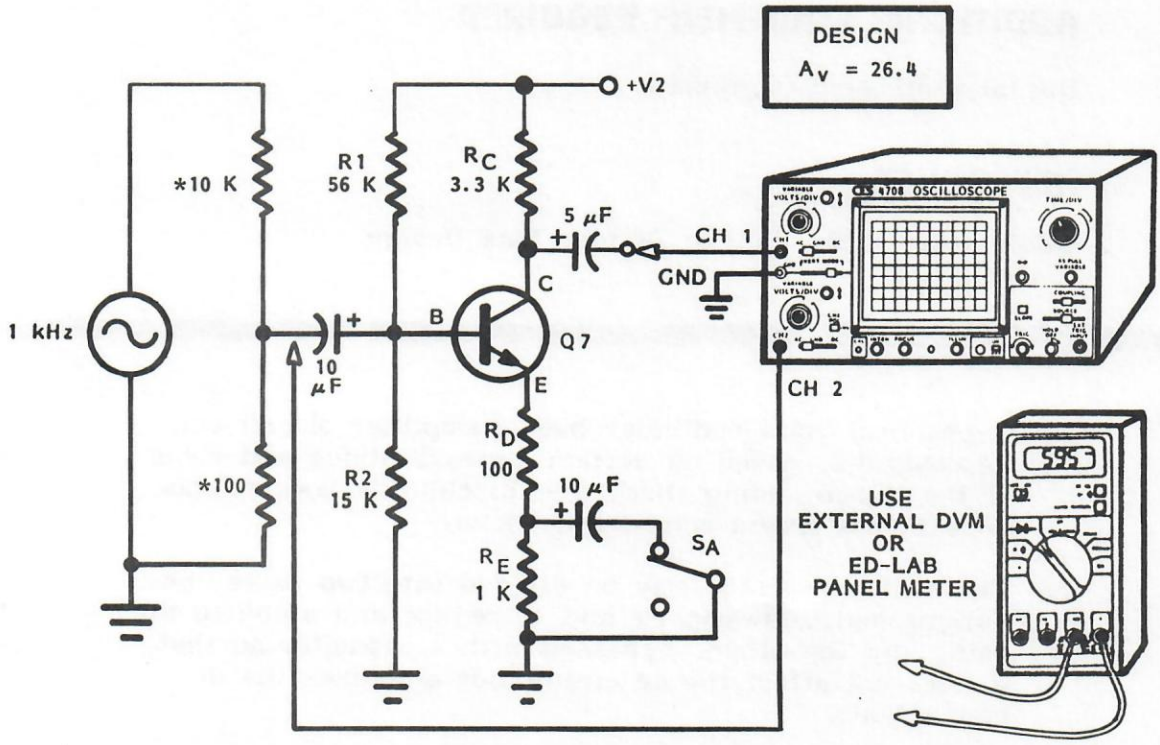
   6.1 Voltage Distribution
   6.2 Circuit Gain Measurements
   6.3 Output Distortion and Clipping
   6.4 Troubleshooting (Optional)

PROCEDURE

6.1 VOLTAGE DISTRIBUTION

In the first part of this experiment we will wire the Voltage Divider Biased amplifier designed in Lesson J1-6 and measure the circuit voltages. The circuit voltages will then be compared to the expected design voltages.

1. Wire the circuit shown in Figure 1. Set switch SA UP.



* NOTE: Not used if trainer has HI-LO switch. Set switch at LO.

Figure 1 - Operational voltage divider biased CE amplifier EXPERIMENT .

2. It is best to use a digital voltmeter to make the voltage measurements listed in Table 1 as the DVM will provide maximum accuracy. If a digital voltmeter is not available, use the Ed-Lab panel meter to measure the voltages. The panel voltmeter will cause a slight error due to meter loading, primarily in the base to emitter reading.

   You may also use the oscilloscope to measure the dc voltages by placing the CH 1 Input Switch on Ground, adjusting the Position Control to place the trace at the bottom of the screen and then placing the Input Switch at DC.

   Set the ac input signal to zero level so that you will only read the dc bias voltage levels.

   Measure the voltages listed in Table 1 and enter the values in the spaces provided.

   Which test instrument was used to measure the dc voltages? _____

VOLTAGE	TEST POINTS	EXPECTED *	MEASURED
V_B	Base to Ground	1.8 V	V
V_E	Emitter to Ground	1.1 V	V
V_C	Collector to Ground	5.7 V	V
V_{CC}	+V2 to Ground	9 V	V
V_{BE}	Base to Emitter	0.7 V	V

* Calculated in Lesson J1-6

TABLE 1 - Voltage distribution for the circuit of Figure 1.

3. Recall that V_{BE} for a silicon transistor will fall between 0.6 to 0.7 volts. Does V_{BE} fall in this range? _____

   The value of V_{BE} should equal the difference between V_B and V_E.

$$V_{BE} = V_B - V_E$$

$$= (\quad) - (\quad)$$

V_{BE} =	V

Does the expected V_{BE} equal the measured value of V_{BE}? _____

You can conclude that the design procedure used, although a series of rules of thumb, results in measured voltages that very closely approximate the calculated design values listed in Table 1 of this experiment and Figure 2 of Lesson J1-6.

6.2 CIRCUIT GAIN MEASUREMENTS

In this part of the experiment we will measure the amplifier stage gain. A single transistor amplifier circuit is called a STAGE so we refer to the gain as the "Stage Gain."

4. Set the Function Generator frequency to 1 kHz and, using the Sine Ampl. control, raise the input signal level to 0.1 volts p-p as indicated on CH 2 of the oscilloscope.

5. Measure the p-p output voltage as indicated on the CH 1 display and record it below.

V_{out} =	V p-p

6. Calculate the measured stage gain from

$$A_v = \frac{V_{out}}{V_{in}} = \frac{(\quad)}{0.1}$$

MEASURED GAIN	A_v =

Is the measured gain close to the expected gain of 26.4 calculated in the preceeding lesson (part C)?

_____

_____

You can conclude that it is possible to design a common emitter voltage divider biased amplifier circuit, without a bias adjusting potentiometer, that is stabilized against changes in beta and transistor.

6.3 OUTPUT DISTORTION AND CLIPPING

In this part of the experiment we will use the dual trace oscilloscope to observe the effects of improper bias and excessive input signals that cause overdrive.

7. Set switch SA DOWN to remove the emitter bypass capacitor from the circuit as shown in Figure 2.

   Move the +V2 connections to +V1 and adjust +V1 to 8 volts as read on the Ed-Lab meter. (The use of 8 volts enables us to view the entire output voltage display on the oscilloscope screen with a 1V/DIV scale.)

8. Move the amplifier input lead, marked X, from the junction of the 10 K and 100 ohm resistors to the full Function Generator output as shown in Figure 2 (or move the HI-LO switch setting to HI).

9. Change the 56 K resistor to the 100 K potentiometer and 2.2 K resistor as shown in Figure 2 so that we can vary the bias setting.

   Move the CH 2 scope lead to the emitter but leave the CH 1 lead on the collector.

10. Set the ac signal input at zero.

    Set the oscilloscope controls as follows:

CH 1 and CH 2 V/DIV	1
CH 1 and CH 2 INPUT SW.	DC
SOURCE	CH 1
VERTICAL MODE	ALT

6—VOLTAGE-DIVIDER BIASED AMPLIFIER OPERATION

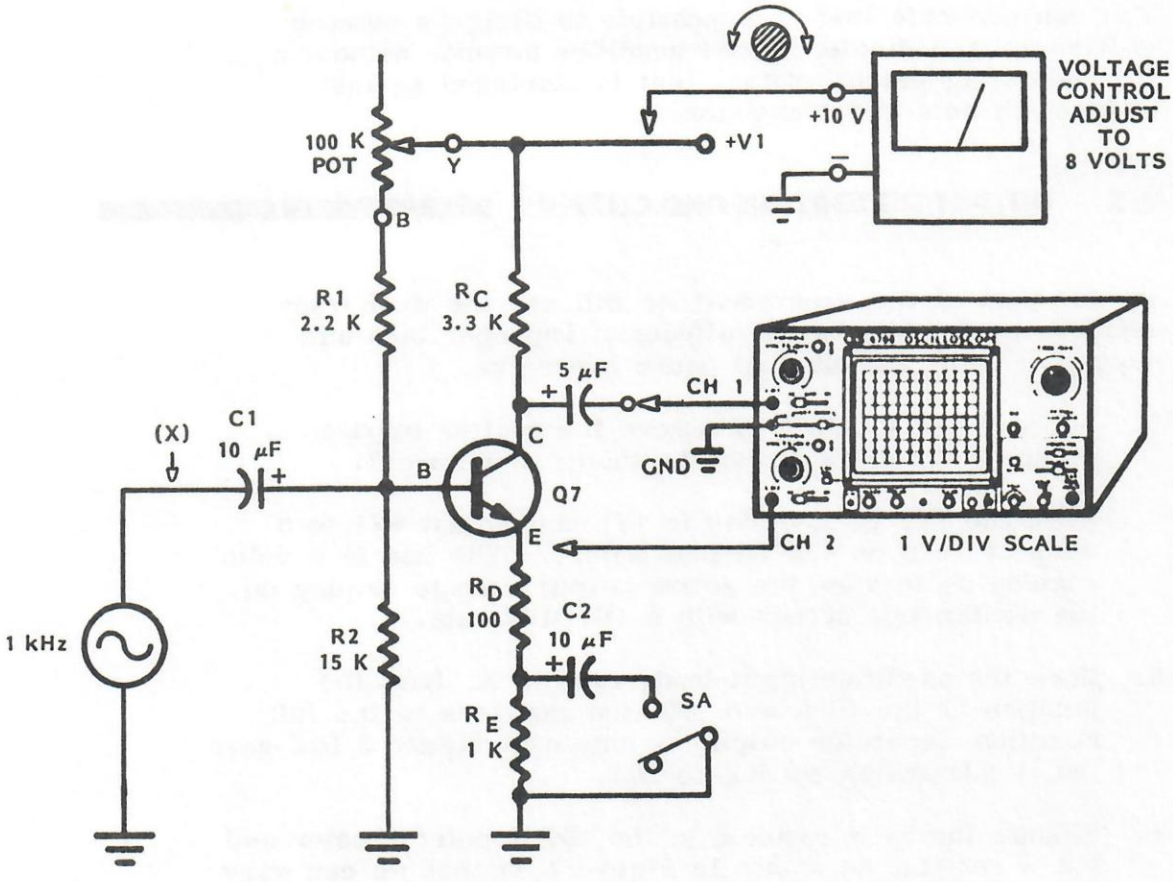


Figure 2 - Variable bias circuit for distortion EXPERIMENT.

11. Set the CH 1 and CH 2 Input Switches to GND and adjust the position controls so that the traces are at 0V at the bottom of the screen graticule. RETURN THE SWITCHES TO DC. Each major screen division equals 1 volt with zero volts at the bottom and 8 volts (V_{CC}) at the top.

    Move the Ed-Lab panel meter from +V1 to the collector and adjust the 100 K pot for a collector dc voltage of 5 volts as read on the meter. You can also view the dc voltage levels of the collector and the emitter on the oscilloscope.

12. Increase the input signal level to obtain the maximum undistorted output signal and record the peak-to-peak value below.

MAXIMUM UNDISTORTED OUTPUT	V_{OUT} = V p-p

13. Increase the input signal so that the amplifier is overdriven and describe what happens to the output signal.

_____

_____

_____

14. Reduce the input signal level to obtain the maximum undistorted output signal again.

Now, vary the 100 K bias pot to increase V_C and describe what happens to the output waveshape.

_____

_____

_____

15. Vary the bias potentiometer to decrease V_C and describe what happpens to the output waveshape.

_____

_____

_____

_____

_____

You can conclude from the above that when the maximum input signal level is exceeded, the output will distort, a condition called "overdrive." The amplifier is said to be "overdriven." Also, if the operating point is moved from the center of the linear region, the output signal will distort at even lower ac input signal levels. The distortion will be clipping at the bottom and top of the sinusoidal waveform.

6.4 TROUBLESHOOTING (OPTIONAL)

16. In troubleshooting, there is a fault in the circuit and the technician or engineer must locate the trouble which is usually a defective part or an open wire or shorted wires. By observing any incorrect waveforms and voltages, we use reasoning to "guess" at what could have caused the incorrect readings based on our knowledge of the theory of circuit operation and on previous experience. Here, we will introduce "known" faults and observe the "incorrect" readings so that later, when a "unknown" fault occurs, we have this previous "experience" on which to base our "guess" or "diagnosis."

Be certain that V_{CC} is still 8 volts and that the 100 K pot is adjusted for a V_C of 5 volts dc. Set switch SA up to insert the bypass capacitor. Set the ac input voltage to 0.1 V p-p, at a frequency of 1 KHz.

Insert the faults in the circuit of Figure 2 as listed in Table 2 by adding a wire lead to the panel (shorting) or by removing a wire lead from the panel (open). For each fault, indicate the effect on the output waveform and measure the base, emitter and collector voltages with respect to ground.

NO.	FAULT	EFFECT ON VOLTAGES			
		V_E	V_B	V_C	AC COLLECTOR OUTPUT
1	No Fault				Normal
2	Shorted B-E				
3	Shorted C-E				
4	Shorted C1				
5	Shorted R_C				
6	Open R_C				
7	Open R1				
8	Open R2				
9	Open C1				
10	Open C2				

TABLE 2 - Troubleshooting chart.

17. Based on your observations, what would you diagnose the fault to be if your measurements showed the following listing in Table 3?

TEST MEASUREMENTS	FAULT DIAGNOSIS
V_B and V_E = 0 V	
V_B and V_E = 0.2 V	
V_E and V_C = 2 V	

TABLE 3 - Troubleshooting problems.

CONCLUSIONS

We have learned from this experiment that:

1. The resistance values necessary for a voltage divider biased transistor amplifier can be calculated using Kirchhoff's and Ohm's Laws and certain "rules of thumb."

2. The emitter circuit resistance can be separated into two parts, a small unbypassed resistance that acts as a swamping resistor and a large, bypassed, resistance that is part of the dc bias circuit only.

3. The stage gain of the common emitter amplifier is calculated from $R_C/(r'e + R_D)$. The value of R_E does not affect the gain because it is bypassed by a large value capacitor.

4. The output signal will distort when there is excessive input signal. This condition is called "overdrive," and the amplifier is said to be "overdriven."

5. The output signal will be distorted if the operating point is moved too far from the center of the linear region.

KEY TERMS

1. BETA (β)

   The current gain of a transistor in the CE configuration. It is equal to the ratio of I_C/I_B.

2. CUT-OFF REGION

   The area of transistor operation where the base current is zero, resulting in no collector current and thus maximum V_{CC}.

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   A loss or deterioration of a function such as amplifier gain. Often deliberately introduced into a circuit in the form of an unbypassed emitter resistor.

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7. OVERDRIVE

   Excessive input signal to the amplifier which drives the output signal into saturation or cut-off or both.

8. r'e

Called R E PRIME, it is the ac resistance of the forward biased base-emitter junction. This ac resistance is approximately equal to $25mV/I_E$ in mA.

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The region of the transistor operation where the base forward bias current is high and I_C has reached its maximum value. Further increases in I_B fail to increase I_C. Also, V_{CE} is very low, no more than several tenths of a volt.

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The ability of an amplifier to maintain its design operating point against changes in temperature and different transistors.

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A resistor placed in series with the emitter that is usually 10 times greater in value than r'e. It minimizes the effect on A_v for any change in r'e. It also causes a reduction in gain.

12. VOLTAGE DIVIDER BIAS

The most often used bias circuit for linear amplifiers. Its name is derived from the resistive voltage divider used to set the base-to-ground voltage.

ASSIGNMENT

Answer the following multiple choice questions.

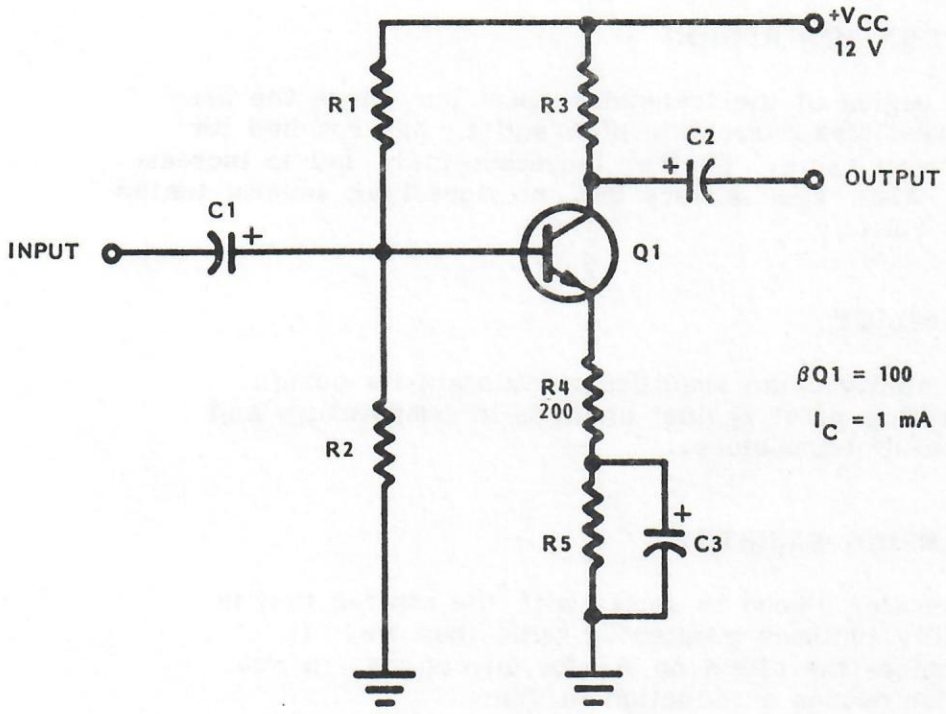


Figure 3 above refers to questions 1 to 15.

1. The voltage from emitter to ground in Figure 3 should be as close as possible to:

   a. 1 volt.
   b. 1.2 volts.
   c. 2 volts.
   d. 12 volts.

2. The value of R5 in Figure 3 should be:

   a. 100 ohms.
   b. 120 ohms.
   c. 1000 ohms.
   d. 1200 ohms.

3. The value of R2 in Figure 3 should be closest to:

   a. 100 K.
   b. 12 K.
   c. 2 K.
   d. 1 K.

4. Given that Q1 in Figure 3 is germanium, the voltage drop across R2 is closest to:

   a. 1.9 volts.
   b. 1.7 volt.
   c. 1.5 volts.
   d. 1.3 volts.

5. The current flow through R2 in Figure 3 is closest to:

   a. 0.1 mA.
   b. 1 mA.
   c. 1.25 mA.
   d. 0.125 mA.

6. The voltage drop across R1 in Figure 3 is:

   a. 10.5 volts.
   b. 11.0 volts.
   c. 11.5 volts.
   d. 12 volts.

7. The Q1 base current, I_B, in Figure 3 is:

   a. 10 μA.
   b. 1 mA.
   c. 1.2 mA.
   d. 100 μA.

8. The best design value for the voltage drop across R3 in Figure 3 is:

   a. one half of V_{CC} .
   b. 1.2 volts.
   c. 5.4 volts.
   d. 1 volt.

9. The ideal value for R3 in Figure 3 is:

   a. 5.4 K.
   b. 10 K.
   c. 5 K.
   d. 12 K.

10. The voltage gain of the amplifier in Figure 3 is:

    a. 4.
    b. 3.
    c. 24.
    d. 44.

11. The voltage gain, for the circuit in Figure 3, when C3 is removed, will change to:

    a. 216
    b. 10.4
    c. 4.4
    d. remain unchanged.

12. If capacitor C3 were disconnected from the junction of R4 and R5, in Figure 3, and connected to the emitter, the gain would:

    a. increase to 216.
    b. increase to 100.
    c. remain the same.
    d. decrease.

13. To overdrive the circuit of Figure 3 means that:

    a. too much input signal voltage is being applied.
    b. the output signal may be driven into saturation.
    c. the output signal may be driven into cut-off.
    d. all of the above.

14. The gain of the circuit of Figure 3 can be increased by:

    a. reducing the value of R4.
    b. increasing the value of R5.
    c. decreasing the value of R2.
    d. all of the above.

15. Shifting the operating point of transistor Q1 in Figure 3 from its optimum setting will:

    a. reduce the stage gain.
    b. reduce the maximum undistorted output level.
    c. increase the maximum undistorted output level.
    d. none of the above.

Input-Output Impedances

Lesson No. 7

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 7, I-O Impedance Measurements.

2. The actual input voltage to a transistor amplifier depends on both the input signal source resistance and the input impedance of the amplifier as well as the input source voltage.

3. The actual output voltage delivered to the load by an amplifier depends on both the amplifier output resistance and the load resistance.

4. The amplifier input impedance of a CE voltage divider biased amplifier equals the parallel combination of the transistor input base resistance, R_{in}, and the two voltage divider resistances in the base bias circuit.

DISCUSSION

An individual amplifier may have a high VOLTAGE GAIN, say 100, when tested by itself as illustrated in Figure 1(b).

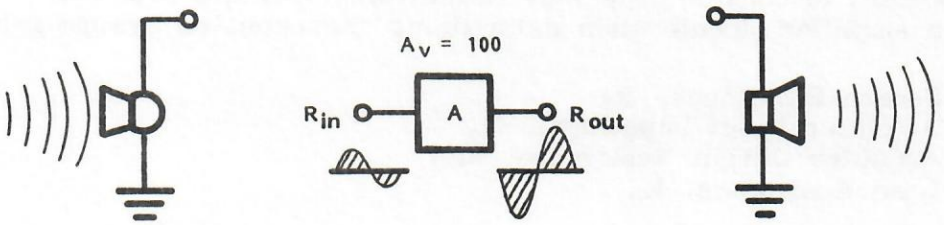


Figure 1 - Amplifier with input source and output load.

A SOURCE such as the microphone, illustrated in Figure 1(a), or any other device, may generate a typical input voltage of 20 mV. The amplifier in Figure 1(b) has to drive a load such as a loudspeaker (c) which has an impedance of 8 ohms.

We might normally expect that with a 20 mV ac input signal and a gain of 100, the ac output voltage will be 2,000 mV or 2 volts. But this does not happen. We might actually measure a 40 mV output which corresponds to a gain of only 2. This happens because the amplifier has an input resistance, R_{in}, which "loads" the source due to the source resistance, R_S, in the voltage divider circuit as shown in Figure 2.

LOADING

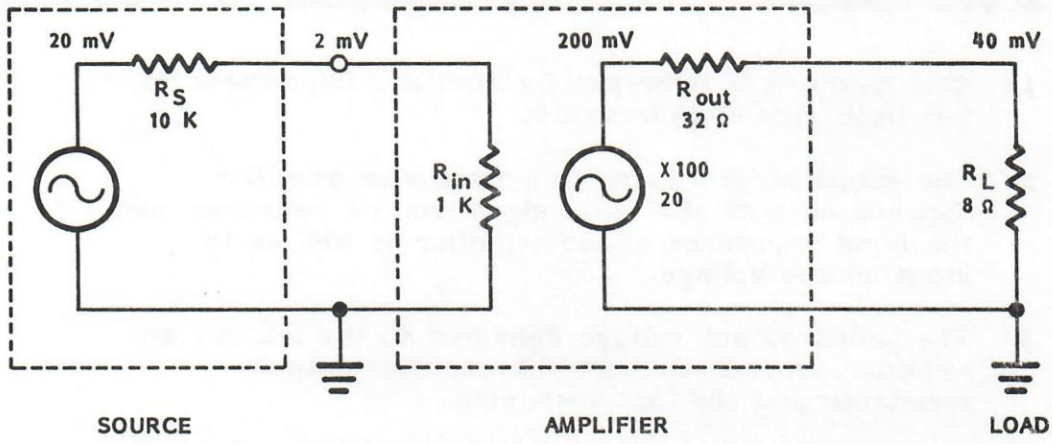


Figure 2 - Amplifier loading effects.

With an unloaded source voltage of 20 mV in the example of Figure 2, the amplifier sees approximately 2 mV at its input because R_{in} is one-tenth of R_S in the source. The amplifier gain of 100 would then generate an output voltage of 200 mV, but, because of the voltage divider action of R_{out} (the output resistance of the amplifier, 32 ohms) and the load resistance, R_L, of 8 ohms, the output is only 40 mV. Thus we only have an overall circuit gain of 2 (from 20 mV to 40 mV) despite an amplifier gain of 100. It is thus important to consider the four measurements or quantities in each amplifier circuit when determining the expected system gain.

a) Source Resistance, R_S
b) Amplifier Input Impedance, Z_{in}
c) Amplifier Output Resistance, R_{out}
d) Load Resistance, R_L

In this lesson we will study the above concepts and learn how to measure these resistances and impedances. When measuring or calculating the circuit impedances the input coupling capacitor, the output coupling capacitor and the emitter bypass capacitor are all considered to have zero ohms reactance. It is assumed that their capacitance values are large and thus, at the lowest frequency of operation, their reactances are equal to almost zero ohms.

In our experiments, the actual ac input resistance of the transistor base circuit, without allowing for the base voltage divider resistances, is defined as R_{in} and is equal to the transistor beta times the sum of r'e and any unbypassed resistors in the emitter circuit. The actual dc input resistance of the base circuit only, as it loads the voltage divider bias network, is defined as R_{IN}. This dc

resistance is equal to the transistor beta multiplied by r'e plus the sum of all resistors in the emitter circuit, bypassed or not.

The circuit input impedance is defined as Z_{in} and is the parallel equivalent of the transistor ac input resistance, R_{in}, and any paralleling circuit components such as the bias network.

These definitions for R_{IN}, R_{in} and Z_{in} are used throughout the experiments that follow. These definitions, however, are not necessarily the same as those used in other texts.

INPUT IMPEDANCE (Z_{in})

The ac signal source that feeds an amplifier provides an input signal current. The amount of input signal current, I_{in}, is a function of the applied signal voltage, the source impedance and the INPUT IMPEDANCE of the amplifier. The amplifier ac input impedance, Z_{in}, is defined as:

$$Z_{in} = \frac{V_b}{I_{in}} \qquad (1)$$

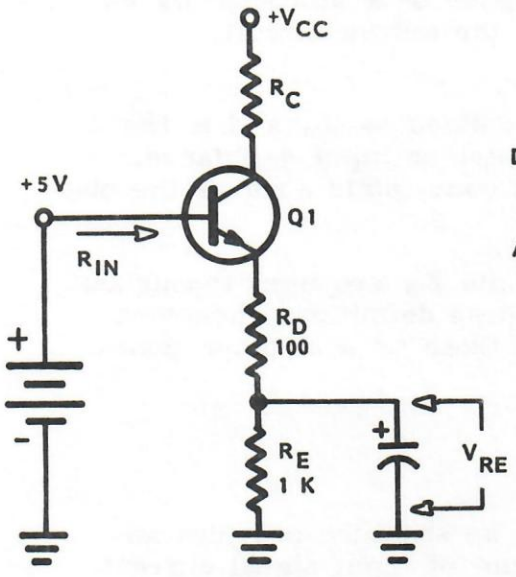
The actual measurement of I_{in} is difficult, requiring opening the connecting wires and special test equipment. As a result, the input impedance of the transistor amplifier is usually calculated from voltage measurements in a circuit under no load and loaded conditions.

INPUT RESISTANCE

The dc input resistance of a transistor, as seen from the base to ground, can be shown to be equal to the current gain, β_{dc}, times the total resistance in the emitter circuit. This was derived in the Information Sheet on Transistor models.

$$\text{Transistor } R_{IN} = \beta R_{E\ TOTAL} \qquad (2)$$

Once R_{IN} is known, the dc base current can be determined as shown in Figure 3. Note that when V_{BE} (0.3 V or 0.7 V) is much smaller than V_{RE}, V_{BE} can be ignored in calculating I_B.



FOR $\beta = 200$

DC $R_{IN} = \beta(R_E + R_D) = (200)(1.1\ K) = \underline{210\ K}$

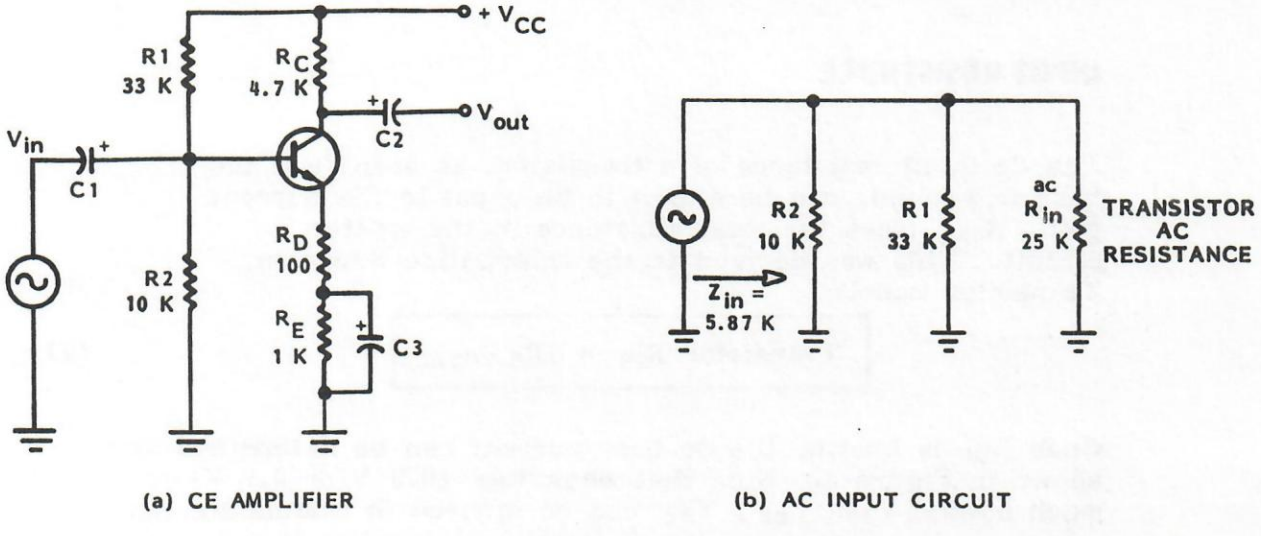
AC $Z_{in} = \beta(R_D + r'e) = (200)(25 + 100) = \underline{25\ K}$

$$I_B = \frac{V_B}{R_{IN}} = \frac{5}{210\ K} \cong \underline{24\ \mu A}$$

Figure 3 - Calculating dc R_{in} and I_B as seen at the base of Q1.

CIRCUIT AC INPUT IMPEDANCE (Z_{in})

When the ac signal is fed to the amplifier input in Figure 4(a), the equivalent resistance or impedance seen is as shown in Figure 4(b). Capacitor C1 is assumed to be large in value with zero reactance and so is not shown in (b).



(a) CE AMPLIFIER

(b) AC INPUT CIRCUIT

Figure 4 - CE circuit and equivalent ac input impedance.

The two voltage divider resistors (R1 and R2) are seen to be in parallel with the transistor ac input resistance. The ac input resistance is equal to $\beta(r'e + R_D)$. The 1 K emitter resistor, R_E, is bypassed by C3 and is not part of the ac input circuit. Thus, for Figure 4:

$$\text{Transistor ac } R_{in} = \beta(25 + 100) = 200\ (125) = \underline{25\ K}$$

Resistor R2, 10 K, is obviously in parallel with the transistor input as seen in Figure 4(a). Resistor R1, 33 K, is in parallel with the transistor input because $+V_{CC}$ is at ac ground potential by virtue of the output filter capacitor of the $+V_{CC}$ power supply, Thus, for the circuit of Figure 4(a) and its equivalent 4(b), the impedance seen by the input generator is:

$$\text{Circuit } Z_{in} = R1//R2//R_{in}$$

where R1 = 33 K; R2 = 10 K; Transistor R_{in} = 25 K

$$\text{Circuit } Z_{in} = 33\ K//10\ K//25\ K = \frac{1}{\frac{1}{33} + \frac{1}{10} + \frac{1}{25}}$$

$$\text{Circuit } Z_{in} = \underline{5.87\ K}$$

OUTPUT IMPEDANCE (R_{out})

The internal resistance of the transistor output collector-to-emitter circuit is very high, 1 megohm or more, because of the reverse biased base-collector junction.

The collector resistance, R_C, which is low, normally between 1 K to 10 K, is in parallel with the junction resistance. It may then be stated that:

$$\boxed{R_{out} = R_C} \qquad (3)$$

EXAMPLE: OVERALL STAGE GAIN

The interaction between the input generator source resistance, R_S, and the input impedance, Z_{in}, the output impedance, R_{out}, and the load resistance, R_L, determine the OVERALL GAIN of the amplifier stage when in a circuit. A typical circuit is shown in Figure 5 with all impedances marked.

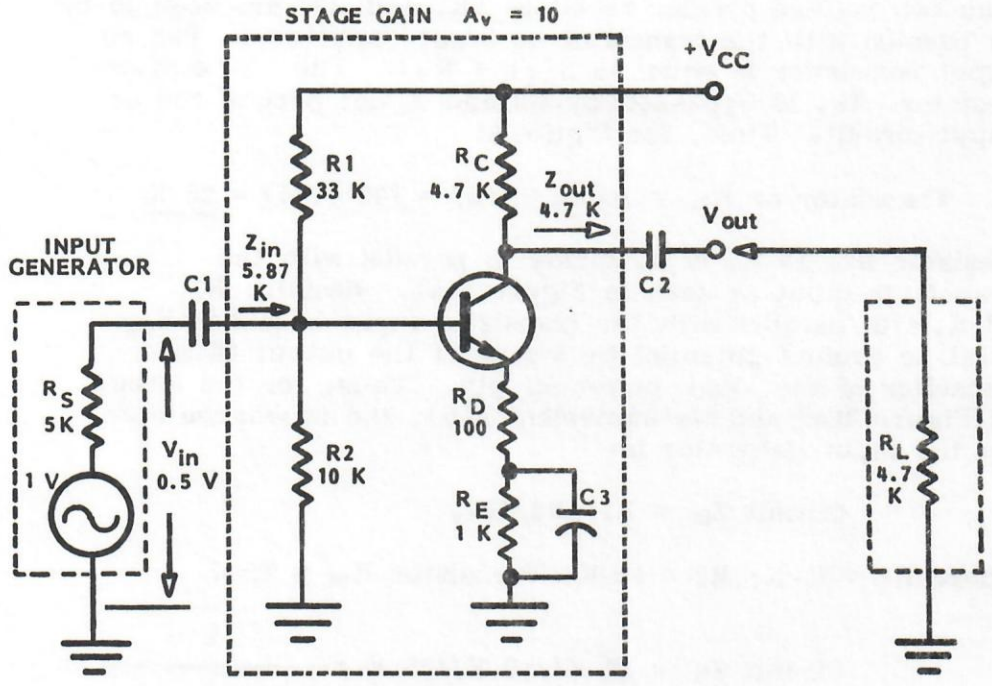


Figure 5 - Input circuit, amplifier and output load.

In the example of Figure 5, we assume a measured or calculated separate amplifier voltage gain of 40 with both input and output impedances equal to approximately 5 K, the signal source, R_S, and the output load also approximately 5 K. When a 1 volt input signal is applied, the signal voltage is cut in half by the voltage divider action of R_S and Z_{in} and the amplifier base sees only 0.5 volts.

The voltage at the output terminal, V_{out}, before R_L is connected, will be:

$$V_{out} = V_{in} A_v$$

$$= 0.5 (40) = \underline{20 \text{ volts}}$$

But when the 5 K LOAD, to which the 20 volts must be delivered to perform some useful work, is connected, it is in ac parallel with R_C, also 5 K. This is true insofar as the ac signal is concerned because C2 blocks the dc path to prevent any change in the V_C bias and the operating point.

The effective value of $R_C//R_L$ is 5 K//5 K or 2.5 K. This drops the gain of the amplifier from 40 to 20. With R_L connected, therefore, the output voltage delivered to the load is:

$$V_{out} = V_{in} \; A_v$$

$$= 0.5 \; (20)$$

$$V_{out} = 10 \text{ volts}$$

The overall stage gain is now 10 with 1 volt in and 10 volts out, and not 40, due to the effects of the source resistance and input resistance voltage divider action and the amplifier output impedance and the parallel load resistance action. For these reasons, it is important to know the input and output impedance of the amplifier and the source and load impedances as well. If the impedances are not taken into account, the lower than expected gain will lead you to believe something is wrong when the stage is operating properly.

KEY TERMS

1. EMITTER SWAMPING RESISTOR

   A resistor placed in series with the emitter that is usually 10 times greater in value than r'e. It minimizes the effect on A_v for any changes in r'e.

2. INPUT IMPEDANCE, Z_{in}

   The impedance seen by a signal source looking into the input terminals of an amplifier circuit.

3. INPUT RESISTANCE, R_{IN}

   The dc resistance seen from base to ground of the transistor amplifier. For a common emitter amplifier circuit it is equal to $\beta(R_E + r'e)$.

4. OUTPUT IMPEDANCE, Z_{out}

   The impedance measured at the output terminals of the amplifier when no load is connected. For a common emitter amplifier, $Z_{out} = R_C$.

ASSIGNMENT

Answer the following multiple choice questions.

1. A signal source with a 2 K internal source resistance has an unloaded output voltage of 300 mV. When loaded by a 1 K input impedance the output voltage will be:

   a. 300 mV.
   b. 200 mV.
   c. 100 mV.
   d. 10 mV.

2. The input resistance of an amplifier can be specified:

   a. as Z_{in}.
   b. as H_o.
   c. in μF.
   d. all of the above.

3. The input impedance of a CE amplifier is equal to:

   a. V_{in} / I_{in}.
   b. Z_{in}.
   c. h_i.
   d. all of the above.

4. A CE amplifier has a 750 ohm unbypassed emitter resistor and a transistor with a beta of 125. The input resistance seen at the transistor base is closest to:

   a. 750 K.
   b. 125 K.
   c. 94 K.
   d. 750 ohms.

5. A common emitter amplifier with voltage divider bias uses two 50 K resistors in the voltage divider circuit and has an input impedance, at the base, of 50 K. The impedance seen by the input generator is:

   a. 16.6 K.
   b. 50 K.
   c. 62.5 K.
   d. 150 K.

I-O Impedance Measurements 7

OBJECTIVES

When you finish this experiment you will be able to:

1. Define what is meant by the dc input resistance, R_{IN}, and the ac input impedance, Z_{in}, of an amplifier stage.
2. Measure the ac input impedance of a common emitter (CE) amplifier stage.
3. Measure the ac output impedance of a common emitter amplifier stage.
4. Measure and compare the voltage gain of an amplifier by itself and in a circuit with voltage losses caused by the amplifier input and output impedances.

REFERENCE

CES Lesson J1-7, Input-Output Impedances

BACKGROUND

1. The dc input resistance of a CE transistor amplifier, R_{IN}, is equal to beta times R_E.
2. The ac input impedance, Z_{in}, of the same CE transistor amplifier is equal to the parallel equivalent of the ac R_{in} to the transistor and the two voltage divider bias resistors.
3. The output impedance of a CE amplifier circuit is equal to R_C.
4. This experiment is in four parts.

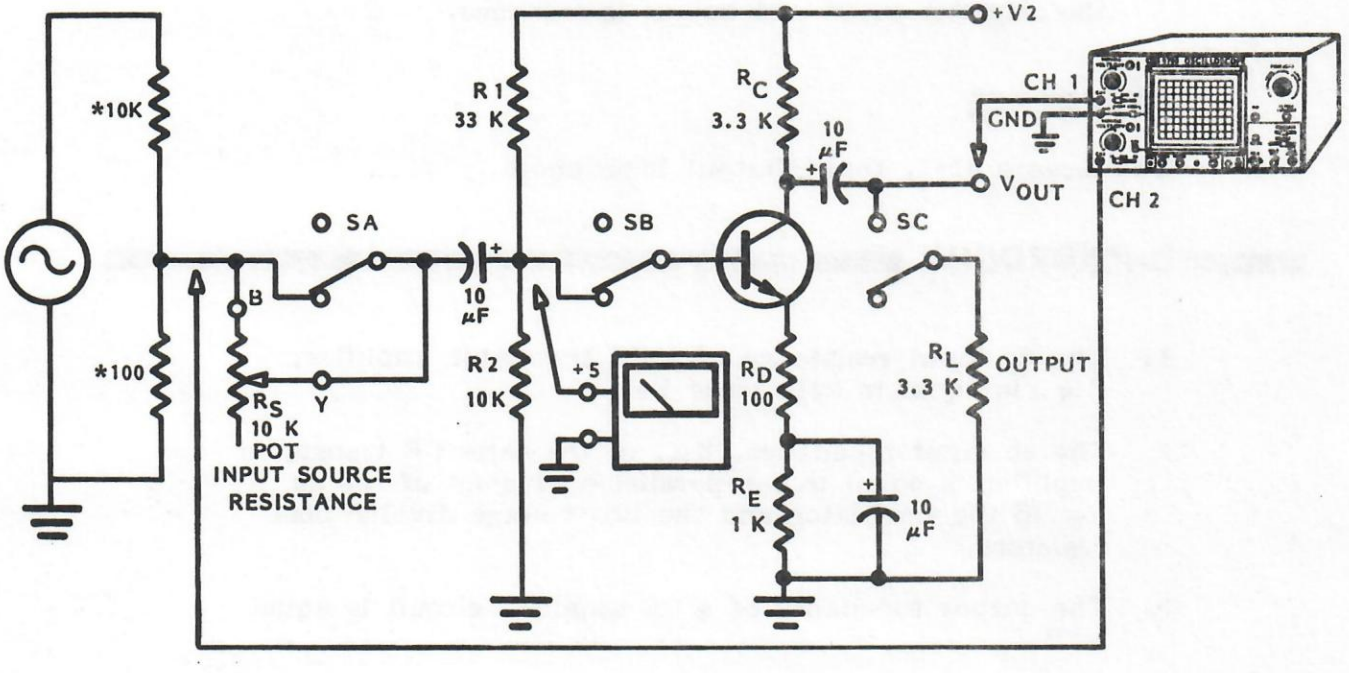
   7.1 Measuring DC Bias and DC R_{IN}
   7.2 Measuring AC Input Impedance, Z_{in}
   7.3 Measuring AC Output Impedance, Z_{out}
   7.4 Measuring Total Stage Gain With Loading

PROCEDURE

7.1 MEASURING DC BIAS AND DC R_{IN}

In the first part of the procedure we will wire a standard common emitter amplifier. We will test the effect of the transistor dc input resistance on the base bias voltage divider to show that it reduces the dc bias voltage by only a small amount. We will then measure the dc R_{IN} of the transistor.

1. Wire the circuit shown in Figure 1.



*NOTE: Not used if trainer has HI-LO switch. Set switch at LO.

Figure 1 - Common emitter amplifier R_{in} and Z_{in} EXPERIMENT.

The circuit wired in Figure 1 is a CE voltage divider biased amplifier with a 100 ohm emitter swamping resistor, and a bypassed 1 K emitter bias resistor.

2. Switch SA is used to provide a variable source resistance, R_S, from 0 to 10 K. Switch SB is used to temporarily disconnect the base from the bias voltage divider so that we can observe the effect of the transistor input resistance on the bias stability and estimate or measure the value of R_{IN}. Switch SC is used to place a 3.3 K load resistor across the output.

Switches SA and SC will be used to measure the effect of the input and output impedances on gain.

Set all switches DOWN to result in an unloaded amplifier so that we can make normal dc bias voltage measurements.

Set the ac input signal to zero.

3. The Ed-Lab panel dc voltmeter, on the +5 volt range, is connected to measure the base voltage derived from the R1-R2 voltage divider circuit. The voltmeter will load the circuit slightly. (The meter internal resistance is 5 x 20 K = 100 K.) The meter will also be used to show how little the transistor input resistance loads the voltage divider. Record the voltage reading below.

V_B WITH TRANSISTOR R_{IN} LOAD	V_B = V

4. Now set switch SB UP to disconnect the transistor input from the voltage divider. Read the new divider bias voltage, V_B, and record it below.

V_B WITHOUT TRANSISTOR R_{IN} LOAD	V_B = V

The loaded voltage divider reading should be only slightly lower because the base input resistance is normally high. Given a typical transistor current gain of beta equals 250, R_{IN} is:

Estimated $R_{IN} = \beta(R_E + R_D) = 250\ (1100) = \underline{275{,}000\ \Omega}$

The value of R_{IN} is very large compared to the 10 K and 33 K voltage divider resistances so the dc base bias voltage change should be small when the transistor R_{IN} loads the divider. Does the transistor input resistance place a large load on the voltage divider circuit?

_____

_____

MEASURING THE TRANSISTOR DC R_{IN}

5. The transistor input resistance, R_{IN}, can be determined by calculation using the loaded and unloaded voltage readings taken on the base voltage divider in steps 3 and 4 earlier. Instead, we will measure the base current flow and determine R_{IN} using Ohm's Law.

   Wire the meter in the 50 μA current range as shown in Figure 2.

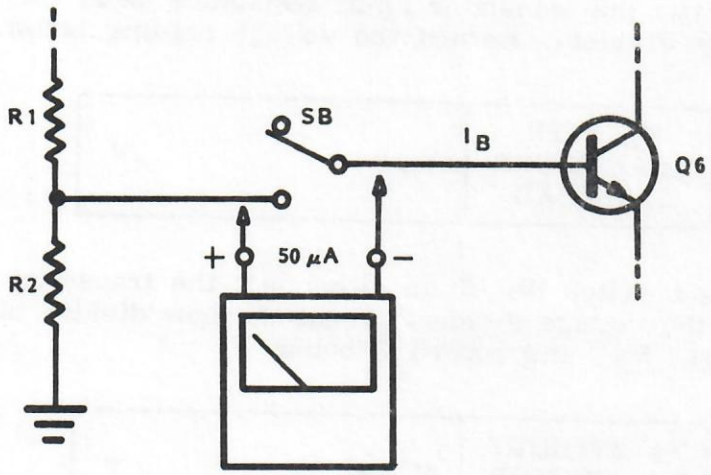


Figure 2 - Measuring I_B of Q6; EXPERIMENT.

Read the current, I_B, from the 50 μA scale with switch SB OPEN (UP). Record I_B below.

MEASURED BASE CURRENT	I_B = μA

Calculate R_{IN} (recalling that V_{IN} is V_B from step 3) from:

$$R_{IN} = \frac{V_{IN}}{I_B} = \frac{(\quad)}{(\quad \mu A)}$$

MEASURED R_{IN}	R_{IN} = K

How close is the measured R_{IN} to the theoretical R_{IN} based on an estimate of the dc beta earlier in step 4?_____

_____

Remove the meter and place switch SB DOWN again to connect the input to the transistor.

You can conclude from the above that the base voltage, V_B, is determined by R1 and R2 in Figure 1 and the base current load, I_B, barely changes V_B. Also, the dc input resistance, R_{IN} is high, equal to $\beta(R_E + R_D)$.

7.2 MEASURING AC INPUT IMPEDANCE, Z_{IN}

In this part of the experiment, we will measure the ac gain of the amplfier with a low value of R_S (100 ohms). We will then insert a larger source resistance to enable the measurement of Z_{in}, the ac input resistance.

6. Set all switches in the DOWN position to result in the standard unloaded amplifier so that we can measure the normal gain. Set the 10 K pot (which is shorted out by SA at this time) to zero ohms by rotating it fully CCW.

7. Adjust the input signal level to 0.02 volts p-p (20 mV p-p) as indicated by the CH 2 oscilloscope display.

   Read the p-p output voltage as indicated on the CH 1 display and record it below.

   For V_{in} = 0.02 V p-p

MEASURED OUTPUT VOLTAGE	V_{out} = V p-p

8. Calculate the voltage gain from:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{(\quad)}{0.02}$$

MEASURED AMPLIFIER GAIN	A_v =

9. We will now measure the input impedance, Z_{in}, as seen by the Function Generator.

   With all switches DOWN and the 10 K pot fully CCW, adjust the input signal level for a fixed output which we select as 0.8 volts p-p. This will be 4 divisions on CH 1 with the V/DIV switch set at 0.2 V.

10. Now place switch SA UP to insert the 10 K pot in series with the signal source.

    Rotate the 10 K pot until the output voltage drops by half and is now 2 divisions.

    This means that half of the previous input signal has appeared at the transistor base. Thus, half the ac input signal is lost across the setting of the 10 K pot. The pot resistance, therefore, must be equal to the ac input impedance, Z_{in}.

11. Estimate the pot resistance by counting the divisions printed on the panel around the 10 K pot knob, each division being equal to 1 K. If an ohmmeter is available, you can measure the pot resistance after disconnecting it from the circuit temporarily. Enter the pot resistance below and check the method used.

    ☐ POT SETTING ☐ OHMMETER

MEASURED INPUT IMPEDANCE	Z_{in} = K

12. The expected theoretical input impedance is the parallel combination of R1, R2 and the ac input, R_{in} of the transistor in the circuit of Figure 1. The theoretical ac R_{in} is equal to:

    Transistor $R_{in} = \beta(R_D) = 250\ (100) = 25$ K

    Thus: $Z_{in} = R1//R2//R_{in}$ [for an estimated beta of 250 while ignoring r'e]

    $= 10\text{ K}//33\text{ K}//25\text{ K}$

ESTIMATED AC INPUT IMPEDANCE	Z_{in} = K

Was the measured input impedance close in value to the expected input impedance?

_____

_____

There will be a small difference between the measured and calculated R_{in} because we estimated beta and ignored r'e.

You can conclude that the input impedance of a transistor circuit reduces the overall gain in combination with the source resistance. The input impedance is estimated as $\beta(R_D)$ in parallel with the bias resistors.

7.3 MEASURING AC OUTPUT IMPEDANCE, Z_{OUT}

In this part of the procedure you will measure the amplifier output impedance as seen by the load, looking at the collector. Z_{out} can be measured in two ways. The impedance, Z_{out}, may be measured using a variable load which is adjusted until V_{out} is half the unloaded value. The resistance of the adjustable load is then equal to Z_{out}. Z_{out} may also be measured by placing any suitable value fixed resistor across the output and then using the voltage divider equation as will be done here.

13. Set all switches in the DOWN position (normal amplifier with no load) and a low R_S of 100 ohms.

    Adjust the input signal level so that V_{out} is again fixed at exactly 0.8 volts (4 divisions at 0.2V/DIV).

14. Set switch SC UP to add the 3.3 K load, R_L, across the output. Measure the reduced or "loaded" output voltage level and record it below.

LOADED OUTPUT VOLTAGE	V_{OUT} = V p-p

15. You will observe that using the 3.3 K load resistance causes the output to drop to one half the unloaded output voltage indicating that Z_{out} is also 3.3K. The ac output impedance of the CE amplifier is equal to R_C.

If a load resistor of any other value is used, Z_{out} can be found from:

$$Z_{out} = R_L \frac{(V_{NL} - V_{FL})}{V_{FL}}$$

where V_{FL} = fully loaded output voltage
V_{NL} = unloaded output voltage

Assuming a V_{NL} of 0.8 volts, a V_{FL} of V_{out} from step 14 and an R_L of 3.3K, we have:

$$Z_{out} = (3300) \frac{(0.8) - (\quad)}{(\quad)}$$

MEASURED OUTPUT IMPEDANCE	Z_{out} = K	AC Z_{out} EQUALS R_C

This same value of Z_{out} will result if we used any value of R_L, say 1 K, 2.2 K, 4.7 K, etc. In some circuits it may not be possible to load the output voltage to half value without upsetting bias voltages when making output impedance measurements so the equation method may have to be used.

The conclusion is that the ac output impedance of a common emitter amplifier, Z_{out}, is equal to the value of R_C, the collector resistance.

7.4 MEASURING TOTAL STAGE GAIN WITH LOADING

In this part of the experiment you will observe that the overall stage gain, from the input signal source to the load, is not as great as the individual amplifier gain measured in part 7.2. You will simulate a signal source with a high source resistance (10 K) and connect a 3.3 K resistor across the output to simulate a load and then determine the overall gain.

16. Place switch SA UP to insert the 10 K pot and rotate the pot fully clockwise to provide a 10 K source resistance. Note from Figure 1, that the V_{in} being measured for this gain is the source voltage before the loading action of the 10 K source resistance in order that we may show the overall effect of input and output amplifier resistances.

Place switch SC UP to add the 3.3 K output load, set V_{in} at 40 mV and measure and calculate the overall stage gain as shown below.

$$A_v = \frac{V_{out}}{V_{in}} = \frac{(\quad)}{0.04}$$

LOADED AMPLIFIER GAIN	A_v =

17. Compare the overall stage gain to the unloaded amplifier gain measured earlier in step 8 where R_S was only 100 ohms. Enter the gain measured in step 8, again, below.

UNLOADED AMPLIFIER GAIN FROM STEP 8	A_v =

There is a loss of voltage gain due to the source and input resistances so that the amplifier never sees the full unloaded input signal voltage. There is another voltage loss due to the load resistance connected to the amplifier output.

Why is the overall stage gain lower when the input source resistance is high and the output loaded? _____

_____

_____

_____

_____

It has been shown that it is normal for the loaded gain of an amplifier to be lower than the unloaded gain. You have also seen that a high source resistance reduces the input signal level, further reducing the output. You can conclude that input and output loading conditions are always important when using amplifiers.

CONCLUSIONS

We have learned from this experiment that:

1. The input dc resistance at the base of a common emitter amplifier is equal to βR_E where R_E is the sum of the swamping resistor and the bypassed bias resistor.

2. It is not unusual for the input dc resistance at the base of a CE amplifier to equal 250 K or more due to the high values of beta.

3. The actual ac input impedance, Z_{in}, of the CE amplifier is equal to the parallel equivalent of the two base voltage divider resistors, R1 and R2 and the ac R_{in}. As a result, Z_{in} is usually less than 10 K in a CE circuit.

4. The ac output impedance, Z_{out}, of the CE amplifier is equal to the value of R_C, the collector resistor.

5. The overall stage gain is lower than the individual amplifier stage gain due to the voltage divider loading effects of the source resistance and the amplifier input impedance.

6. The overall stage gain is also lower than the individual amplifier stage gain because the paralleling effect of the output impedance and the output load impedance.

KEY TERMS

1. EMITTER SWAMPING RESISTOR

   A resistor placed in series with the emitter that is usually 10 times greater in value than r'e. It minimizes the effect on A_v for any changes in r'e.

2. INPUT IMPEDANCE, Z_{in}

   The impedance seen by a signal source looking into the input terminals of an amplfier circuit.

3. INPUT RESISTANCE, R_{IN}

   The dc resistance seen from base to ground of the transistor amplifier. For a common emitter amplifier circuit it is equal to β multiplied by the sum of all the resistances in the emitter circuit ($R_E + R_D + r'e$).

4. LOAD

   A device or component that absorbs power from the amplifier and changes its form. A speaker load, for example, changes the electrical power to sound power while a resistive load changes the power to heat.

5. OUTPUT IMPEDANCE, Z_{out}

   The impedance measured at the output terminals of the amplifier when no load is connected. For a common emitter amplifier $Z_{out} = R_C$.

6. SOURCE RESISTANCE

   The internal series resistance of a voltage source.

ASSIGNMENT

Answer the following multiple choice questions.

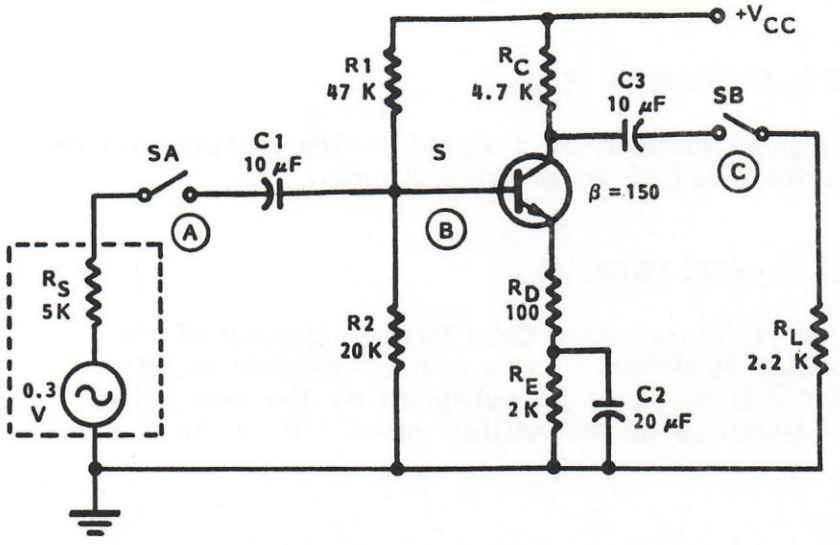


Figure 3 above refers to questions 1 to 10.

1. The dc input resistance of the transistor base circuit (neglecting the parallel effects of R1 and R2) is approximately:

   a. 2,100 + r'e.
   b. 315 K.
   c. 67 K.
   d. 6.8 K.

2. The ac input impedance of the transistor base circuit (neglecting the parallel effects of R1 and R2), given that r'e is 25 ohms, is approximately:

   a. 315 K.
   b. 18.75 K.
   c. 2,125 ohms.
   d. none of the above.

3. The input impedance, Z_{in}, as seen by the input generator is approximately:

   a. 47 K.
   b. 20 K.
   c. 8 K.
   d. 2.1 K.

4. Given an input impedance of 10 K at point A in Figure 3 and an unloaded source voltage of 0.3 volts, the signal voltage at point A, when switch SA is closed, will be approximately:

   a. 0.3 volts.
   b. 0.15 volts.
   c. 0.1 volts.
   d. 0.2 volts.

5. The theoretical unloaded gain of the amplifier shown in Figure 3 (ignoring r'e) is closest to:

   a. 2.2.
   b. 23.5.
   c. 47.
   d. 150.

6. If capacitor C2 is removed from the circuit of Figure 3, the theoretical unloaded amplifier gain will change to:

   a. 2.2.
   b. 23.5.
   c. 47.
   d. remain the same.

7. Given the following data for transistor Q1 in Figure 3, I_E = 1 mA; V_{BE} = 0.65V, the voltage drop across R2 is:

   a. equal to the voltage drop across R1.
   b. equal to the voltage drop across R_C.
   c. 0.65 volts.
   d. 2.75 volts.

8. The gain of the amplifier stage in Figure 3, with switches SA and SB closed, is closest to:

   a. 1.1.
   b. 15.
   c. 38.
   d. 100.

9. The output voltage in Figure 3, with all switches closed, assuming a Z_{in} of 10 K, will equal:

   a. 0.3 volts.
   b. 0.6 volts.
   c. 3 volts.
   d. 6 volts.

10. Increasing the value of R_E in Figure 3 will:

    a. increase the dc R_{IN} at the base, point B.
    b. not affect the value of ac Z_{in} at B.
    c. increase V_E and V_{R2}.
    d. all of the above.

Characteristic Curves 8

OBJECTIVES

When you finish this experiment you will be able to:

1. Plot the output characteristic curves for the collector circuit of a CE amplifier.
2. Plot a load line on the collector characteristic curves.
3. Calculate the ac beta and dc beta values from the collector characteristic curves.
4. Locate an operating point or quiescent point on the load line.
5. Display the collector characteristic curves for various values of base current on an oscilloscope screen using the X-Y mode.
6. Display an amplifier circuit load line on the oscilloscope screen.
7. Demonstrate the effect on the load line slope when the value of the collector load resistor is varied.
8. Display a complete family of curves on the oscilloscope.

REFERENCE

Information Sheet 2, Transistor Characteristic Curves

ADDITIONAL EQUIPMENT REQUIRED

a. Digital Voltmeter
b. IC Binary Counter Chip 7493 (Optional)

BACKGROUND

1. The transistor has three terminals; base, emitter and collector. In the common emitter configuration, the input is connected to the base and the output is taken from the collector and the emitter is common to both the input and output circuits. There are two curves that may be plotted which represent this circuit. The input curve is a plot of the base-emitter current versus base-emitter voltage. The output curve is a plot of

collector-emitter current versus collector-emitter voltage. The output curves, called the CE CHARACTERISTIC CURVES, are actually a set of curves, each for a different base current.

2. The set of collector characteristic curves help us to understand how beta is derived, how beta is not a constant but varies with collector current, how the operating point is established with a LOAD LINE, how saturation occurs, how cut-off occurs and, how distortion occurs.

3. This experiment consists of five parts. These are:

   1. CE Characteristic Curves
   2. Beta Calculations
   3. Load Line and Operating Point
   4. Set of Characteristic Curves and Load Line
   5. Characteristic Curve Tracer (Optional)

PROCEDURE

8.1 CE CHARACTERISTICS CURVES

In this first part of the experiment we will set I_B to two values and plot I_C versus V_{CE} for each. We will, in the following parts, use the data to calculate the dc beta and ac beta. A load line will then be used to select the optimum operating point.

1. The transistor circuit shown in Figure 1 enables us to vary I_B and V_{CE} so that I_C versus V_{CE} may be plotted. The circuit provides control of the base current by varying the 1 meg pot and control of V_{CE} by varying the +V1 variable voltage source. A digital multimeter connected to switch SA is switched down to measure V_{CE} and up to read the voltage drop across R_C, (V_{RC}) which gives the collector current based on $I_C = V_{RC}/R_C$.

   Wire the transistor test circuit shown in Figure 1.

2. CURVE AT 20 MICROAMPERES: Set the 1 K pot collector resistance to zero (CCW). Adjust the base current, I_B, (using the 1 meg pot) to read 20 μA on the Ed-Lab panel meter.

3. With switch SA DOWN, vary V_{CE} (+V1 voltage control) to read the values of voltage listed in Table 1. For each value of voltage listed, set switch SA UP to read current (V_{RC}) on the digital meter and enter the results in Table 1.

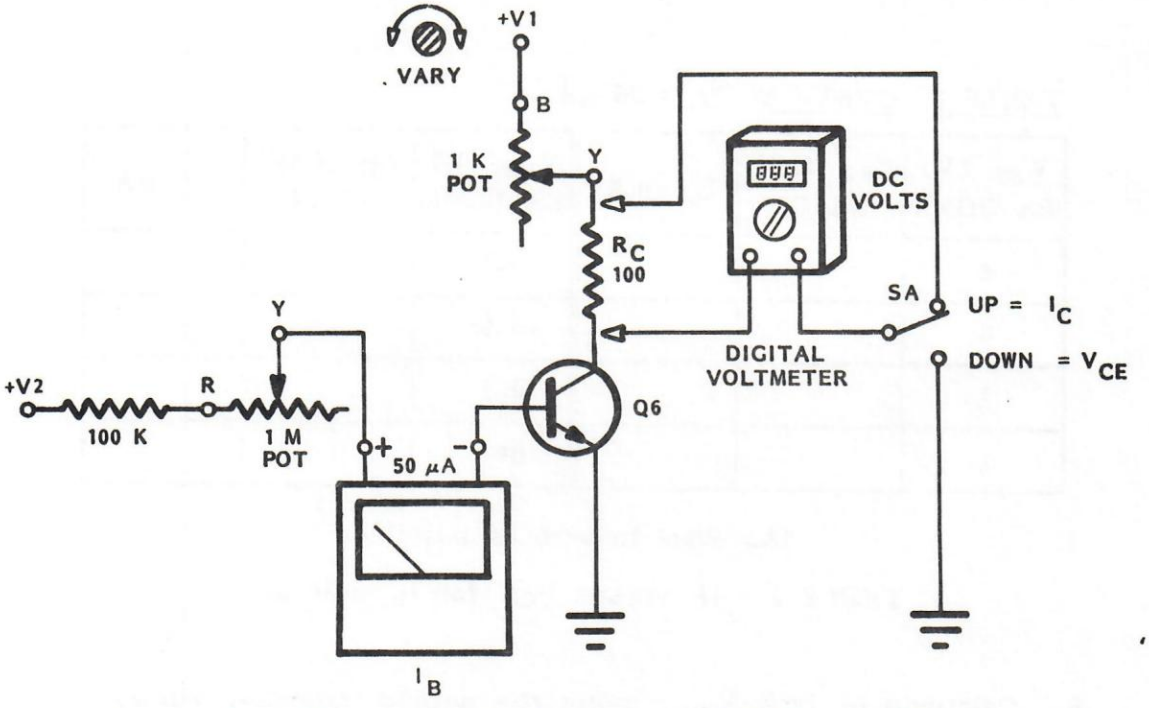


Figure 1 - CE characteristic curve plot EXPERIMENT.

TABLE 1 CURVE A I_B = 20 μA

V_{CE} (V) SA DOWN	V_{RC} (mV) SA UP	I_C (mA)	V_{CE} (V) SA DOWN	V_{RC} (mV) SA UP	I_C mA
8			0.3		
6			0.2		
3			0.1		
1			0*		

*As close to zero as possible.

TABLE 1 - I_C versus V_{CE} for I_B = 20 μA.

4. CURVE AT 30 MICROAMPERES: Be sure that the 1 K pot collector resistance is at zero. With switch SA DOWN, set V_{CE} to 8 volts and adjust the base current (I_B) to 30 microamperes as indicated on the Ed-Lab panel meter. Readjust V_{CE} as necessary.

5. With switch SA DOWN, vary V_{CE} to read the values of voltage listed in Table 2. Read V_{RC} (switch SA UP) and enter the results in Table 2.

TABLE 2 CURVE B I_B = 30 μA

V_{CE} (V) SA DOWN	V_{RC} (mV) SA UP	I_C (mA)	V_{CE} (V) SA DOWN	V_{RC} (mV) SA UP	I_C mA
8			0.3		
6			0.2		
3			0.1		
1			0*		

*As close to zero as possible.

TABLE 2 - I_C versus V_{CE} for I_B = 30 μA.

6. Calculate I_C from V_{RC}, using the method indicated below, for both tables and enter the results in the remaining columns. Note that V_{RC} is dropped across 100 ohms and $I_C = V_{RC}/100$. Thus, if V_{RC} = 350 mV then I_C = 350/100 equals 3.5 mA and the computation requires only a shift of the decimal point two places to the left.

7. Plot the results from Tables 1 and 2 on the graph in Figure 2. Note that the graph already has a "Load Line" for R_C = 1 K (the dashed line). The V_C intercept point is 9 volts and the I_C intercept, V_{CC}/R_C = 9/1 K = 9 mA.

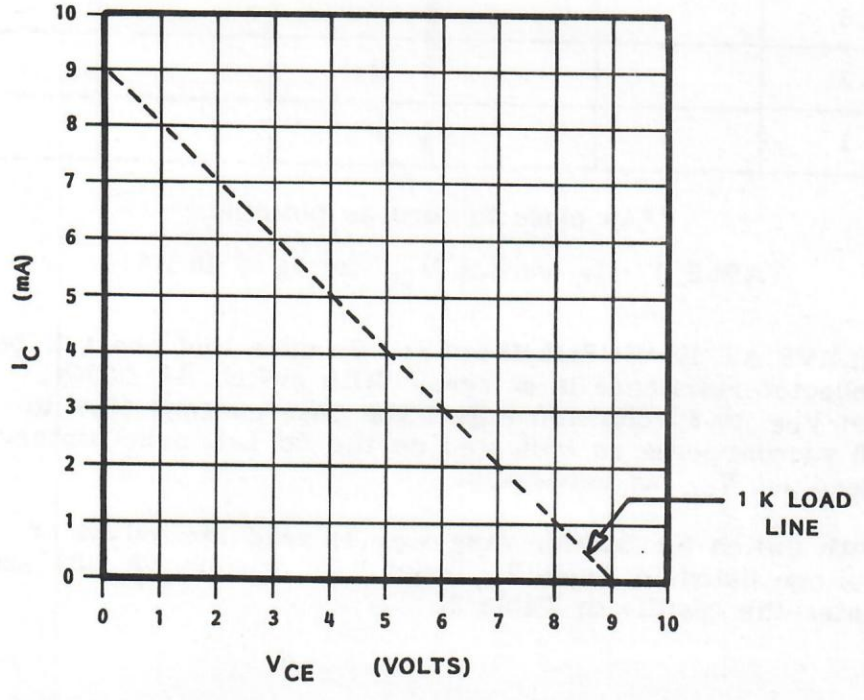


Figure 2 - Graph plot of V_{CE} versus I_C for I_B = 20 μA, and 30 μA.

In this part of the experiment you have gathered sufficient data to plot two collector characteristic curves and to calculate the transistor's dc beta and ac beta which will be done in the next part of the experiment.

8.2 BETA CALCULATIONS

In this part of the experiment you will calculate the transitor dc beta and ac beta values and compare them. You will observe the effect of I_C on the dc beta value.

8. The transistor dc current amplification (β_{dc}) can be determined from the collector curves plotted on the graph in Figure 2 or from the data in Tables 1 and 2.

   The DC BETA is obtained from the ratio of I_C to I_B at a given value of I_B and V_{CE}. Calculate the dc beta for both I_B = 20 μA and I_B = 30 μA at the arbitrary V_{CE} of 3 volts from:

$$\beta_{dc} = \frac{I_C}{I_B}$$

I_B = 20 μA; V_{CE} = 3 V	$\beta_{dc} = \frac{(\quad)}{(\quad)} =$
I_B = 30 μA; V_{CE} = 3 V	$\beta_{dc} = \frac{(\quad)}{(\quad)} =$

DC BETA

   Note that at a base current of 30 μA, which results in a higher I_C, dc beta is higher.

9. The AC BETA is obtained from the ratio of the "change" in I_B (ΔI_B) and the corresponding change in I_C (ΔI_C). This value of beta applies to the ac current and voltage gains in an amplifier stage.

   Calculate the ac beta at the arbitrary V_{CE} value of 3 volts from:

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}$$

V_{CE} 3V	$\beta_{ac} = \frac{(\quad) - (\quad)}{(\quad) - (\quad)} = \beta_{ac} =$

AC BETA

You can conclude from the above that the dc beta increases as I_C increases and that the dc and ac beta values also differ. We did not test ac beta at different values of collector current but ac beta also varies for different I_C values.

8.3 LOAD LINE AND OPERATING POINT

In this part of the experiment we will check to see if the collector-to-emitter voltages, V_{CE}, determined by the intersect points of the CE curve and the load line for an R_C of 1 K, as determined from Figure 2, agree with the measured V_{CE} values for given base currents for the transistor circuit.

10. Circle the intersect points (operating points or Q points) of both collector characteristic curves and the 1 K load line for the 20 μA and 30 μA base currents.

11. Use the same experiment circuit as shown in Figure 1 but set the collector resistance 1 K pot to maximum (CW) so that we have a load line.

12. Set +V1 to maximum (V_{CC} = 9 volts).

    Adjust the base bias current to 30 μA as indicated on the Ed-Lab panel meter.

13. Set switch SA DOWN to measure V_{CE} on the digital meter and enter the reading in the space provided directly below:

MEASURED	V_{CE} = V
GRAPH (FIGURE 2)	V_{CE} = V

Read the expected value of V_{CE} from the graph in Figure 2 at the point where the 30 μA collector curve intersects the 1 K load line. Enter the result in the space provided above.

How do the measured and expected voltages compare? _____

_____

The measured and graph values of V_{CE} for the 20 μA base current will also be very close in value. You may try this test as well.

You have seen, in this part of the experiment, that the collector characteristic curves and collector resistor load line determine the operating bias point or Q point and V_{CE} for a given base current.

8.4 SET OF CHARACTERISTIC CURVES AND LOAD LINE

In this part of the experiment you will develop a set or "family" of collector characteristic curves using the oscilloscope. You will then determine the ac beta from these curves. The characteristic curves will be plotted on the oscilloscope using the X-Y mode.

14. The circuit of Figure 3 uses the 60 Hz ac source voltage to apply a varying V_{CE} to the transistor. The collector current is measured by the use of small 50 ohm series emitter resistance. The oscilloscope circuit automatically plots the CE collector characteristic curve for the base current that is set by +V1. Using a 4.7 K shunt resistor across the microammeter provides a range on the meter of 0 to 100 μA to read the base current. By correctly setting the X and Y scales, as specified later, the curves will have calibrated scales that can be read on the oscilloscope screen.

    Remove all previous wiring. Wire the circuit shown in Figure 3.

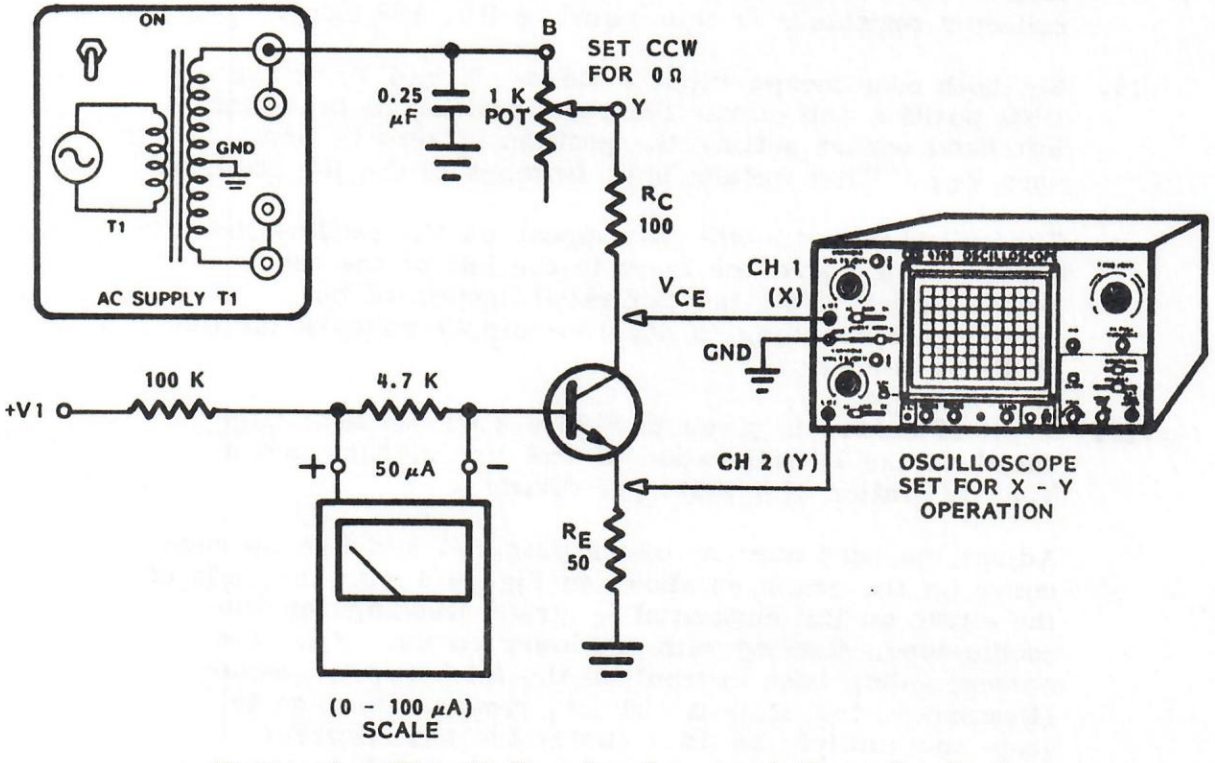


Figure 3 - Circuit for visual presentation of collector characteristic curve; EXPERIMENT.

15. Set the oscilloscope controls as follows:

(CH1) X	2V/DIV
(CH2) Y	0.1V/DIV
TIME/DIV	X - Y

The Y scale is set at 0.1 volts per division across a 50 ohm resistor, which by Ohm's Law is:

$$I = \frac{V}{R} = \frac{0.1}{50} = 2 \text{ mA/DIV}$$

The X and Y scales are thus:

X SCALE	V_{CE}= 2 V/DIV
Y SCALE	I_C = 2 mA/DIV

Rotate the 1 K pot fully CCW for zero ohms. The total collector resistance is thus equal to RC, 100 ohms.

16. Set both oscilloscope Input switches, X and Y, to the GND position and adjust the beam position to the lower left hand corner setting the position of zero I_C and zero V_{CE}. Then return both switches to the DC position.

The collector curve will now appear on the oscilloscope screen. Disregard the trace to the left of the zero points (which is off the calibrated portion of the screen corresponding to negative supply voltages for the 60 Hz ac source).

17. A set of curves is given in Figure 4 on the next page based on the I_C calibration of 2mA per division and a V_{CE} calibration of 2 volts per division.

Adjust the base current by varying +V1 and line up each curve on the graph as shown in Figure 4 with the ends of the curve on the horizontal I_C graph markings on the oscilloscope, starting with the lower curve. Read the corresponding base current on the Ed-Lab panel meter. (Remember, full scale is 100 μA, read on the 0 to 10 scale and multiply by 10.) Enter the base current readings, I_B, on the right side of the graph in the space provided.

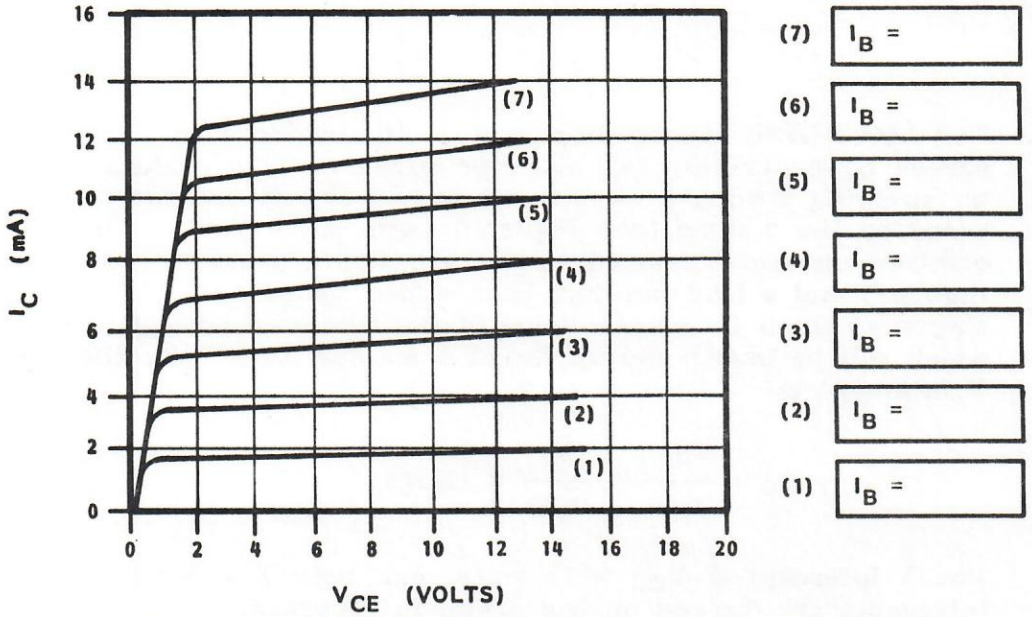


Figure 4 - Set of characteristic curves; EXPERIMENT.

18. Calculate the ac beta by taking the collector current difference between any two collector curves and the corresponding I_B readings at typically V_{CE} , 8 volts.

Use the data from the base current curves (1) and (7) to obtain an average beta at V_{CE} = 8 volts. Calculate the ac beta from:

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B} = \frac{(I_{C7}) - (I_{C1})}{(I_{B7}) - (I_{B1})} = \frac{(\quad) - (\quad)}{(\quad) - (\quad)}$$

$$\beta_{ac} = \frac{(\quad)}{(\quad)} \qquad \boxed{\beta_{ac} =}$$

This part of the procedure used the oscilloscope to display the collector characteristic curves for various base currents. The ac beta was then calculated using the developed family of curves.

8.5 LOAD LINE DISPLAY

In this part of the experiment you will display the LOAD LINE on the oscilloscope screen. You will vary the value of the load resistance, the 1 K pot, and observe how it affects the slope of the load line as displayed on the screen.

19. The LOAD LINE can be displayed on the oscilloscope screen by generating two collector curves. This is done by applying a square wave input to the circuit presently wired on the trainer from Figure 3 (with R_C = 1 K). The collector curves developed earlier are shown again in Figure 5 and a load line has been added based on V_{CC} = 15 volts (the peak value of the 60 Hz ac voltage which will be used) and an R_C of 1 K. For R_C = 1 K, the Y intercept is:

$$I_C = \frac{V_{CC}}{R_C} = \frac{15}{1\ K} = 15\ mA$$

The X intercept is V_{CC} = 15 volts, and both X and Y intercepts are marked on the graph in Figure 5.

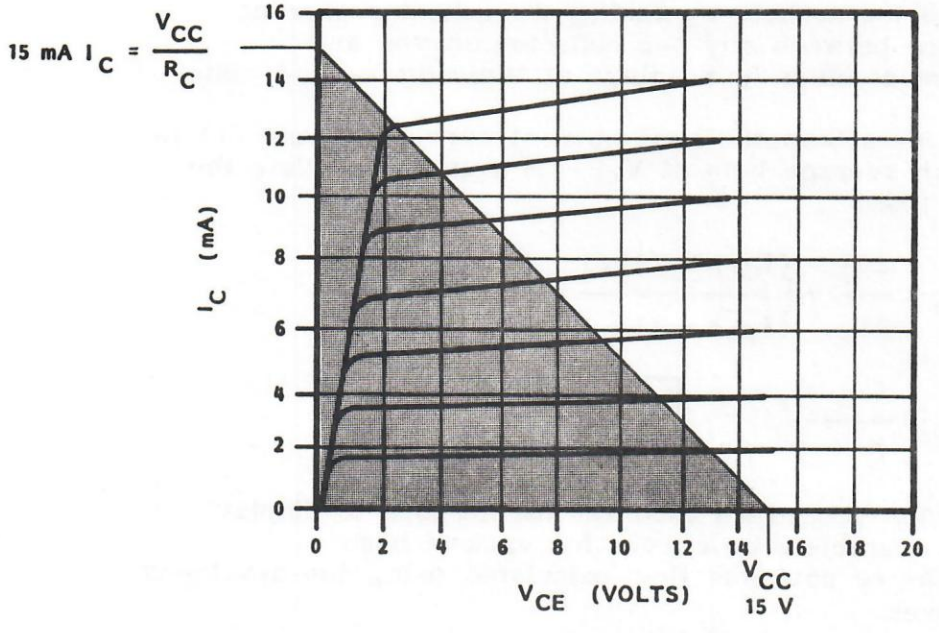


Figure 5 - Collector curves with load line for R_C = 1 K.

20. Connect the square wave to the base circuit as shown in Figure 6 by the darkened lines, using three wires as marked.

Set the frequency to approximately 30 Hz and set the 1 meg pot to mid-point, 500 K.

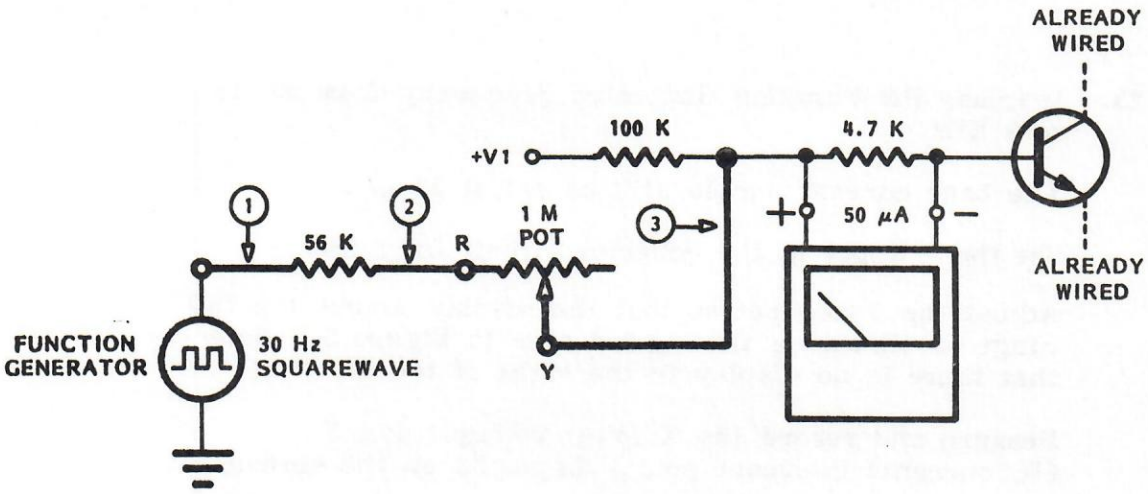


Figure 6 - Circuit addition to display the load line; EXPERIMENT.

21. Adjust the +V1 control to set the base current to 30 μA as indicated on the 100 μA Ed-Lab panel meter (0 to 10 scale x 10).

    Observe that two collector curves are now displayed. The bottom curve represents the zero level of the square wave and the upper curve represents the positive level of the square wave.

22. Decrease the resistance of the 1 meg pot (CW) to increase base current due to the square wave input. How does this affect the display?

    _____

    _____

    _____

    _____

    Increase the +V1 voltage level (CW). How does this affect the display?

    _____

    _____

    _____

    _____

    Return the bias current to the 30 μA setting.

23. Increase the Function Generator Frequency from 30 Hz to 3 KHz.

The base current should still be set at 30 μA.

Set the 1 K pot in the collector circuit fully CW.

Adjust the 1 meg pot so that the display covers the full range as shown by the shaded area in Figure 5. Note that there is no display to the right of the load line.

Measure and record the X (V_{CE} voltage) and Y (I_C current) intercept points displayed on the screen.

SCREEN DISPLAY	X intercept =	V
	Y intercept =	mA

Do the X and Y intercept points agree with the theoretical plot shown in Figure 5? _____

24. Set the 1 K pot fully CCW for zero resistance. How does it affect the slope of the load line?

_____

_____

Increase the resistance of the 1 K pot slowly and observe the effect on the slope of the load line. Describe what happens.

_____

_____

_____

You have seen in this part of the experiment how we were able to display the common emitter amplifier collector characteristic curves and load line on the oscilloscope screen using a square wave input to provide a step in base current and an ac collector voltage to sweep the collector-emitter voltage. When the load resistance, R_C, was dropped to zero ohms, the load line was vertical. As R_C was increased in value, the slope of the load line tilted down towards the horizontal direction.

8.6 CHARACTERISTIC CURVE TRACER (OPTIONAL)

A complete family of many characteristic curves can be plotted on an oscilloscope screen simultaneously. The family of curves is usually plotted using a test instrument called a Characteristic Curve Tracer. We will build a circuit on the trainer for an 8 Curve display. This will be accomplished by using the Function Generator sine wave to provide the varying collector voltage and by using a "3-bit binary counter integrated circuit" (inserted into the panel IC socket) to step the base current for different curves.

25. The circuit to be wired is shown in Figure 7. The digital IC to be inserted in the socket is the "4-bit binary counter", 7493. The three resistors marked R1, R2 and R3 control the base current for the steps between the curves. The variable supply, +V1, also varies the base current. The panel meter reads the base current on a 100 μA scale. The 1 K pot is the collector load resistor and transistor Q5 is the transistor under test (often labelled TUT). Transistor Q7 is used to "blank" the return trace on the oscillocope screen. The square wave output of the Function Generator triggers the binary counter and the Q7 blanking transistor.

26. Wire the circuit shown in Figure 7.

27. Set the oscilloscope controls as follows:

TIME/DIV	X-Y	
CH 1	1 V/DIV	V_C SCALE X
CH 2	0.1 V/DIV	I_C SCALE Y

This results in a Y scale (CH 2) of:

$$I_C = \frac{0.1\ V}{50}\ /DIV = 2\ mA/DIV$$

28. Set the +V1 voltage control to zero (CCW).
Set the -V1 voltage control to zero (CCW).
Set the 1 K pot to zero (CCW).

Set the Function Generator to 1 KHz and the Sine Ampl. to maximum (full CW).

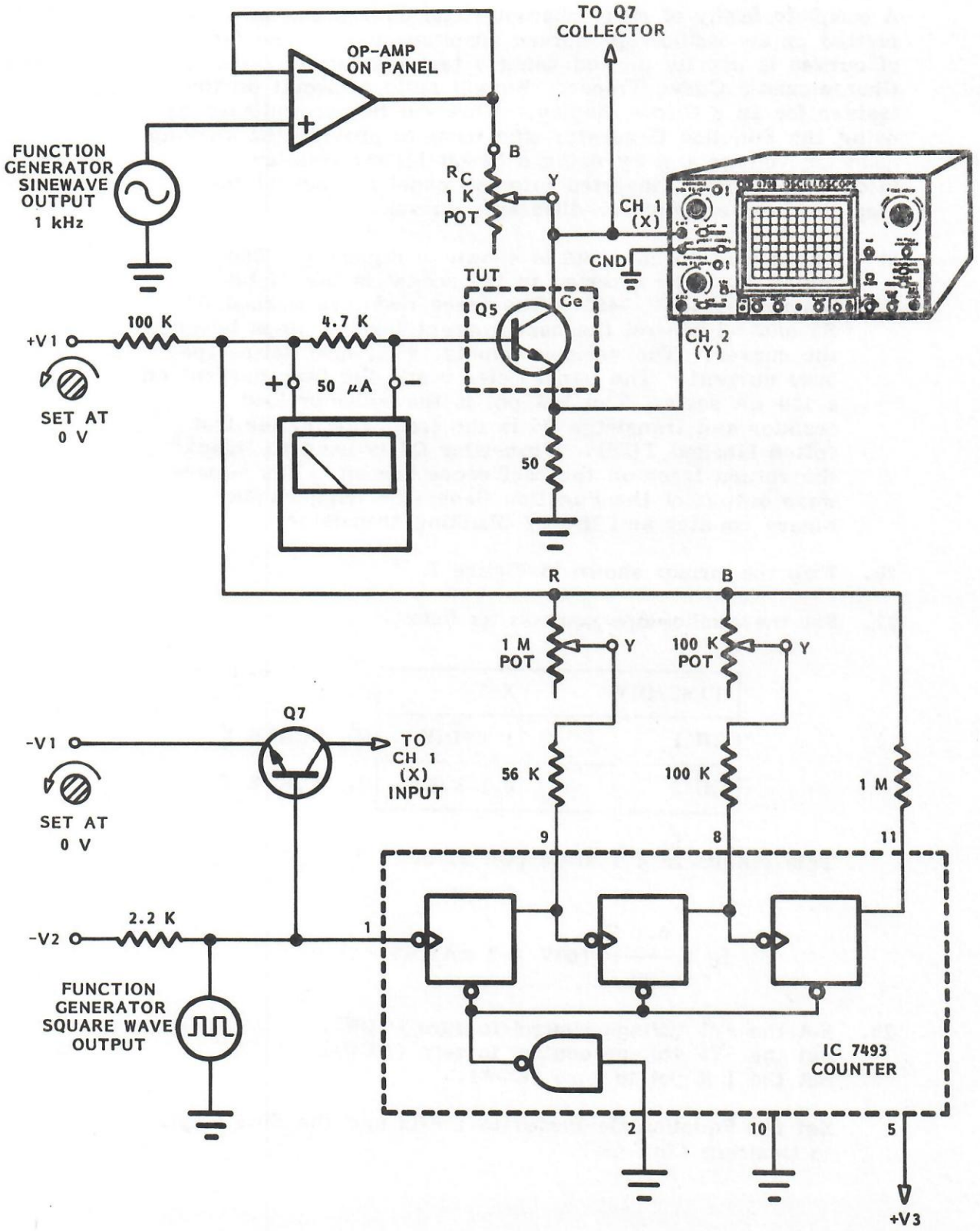


Figure 7 - Characteristic Curve Tracer circuit; EXPERIMENT.

Adjust the following controls to produce a good set of curves.

a) 1 Meg Pot; b) 100K Pot; c) +V1 Supply

29. Adjust the -V1 voltage control to slightly above zero volts to eliminate the bright spot on the bottom left of the screen.

30. Vary the 1 K pot to observe the load line.

31. You can determine the base current for each curve by momentarily removing the lead from IC pin 1. The counter will stop and only a single curve will be displayed. The meter will then read the base current for that single curve. By repeating the above procedure, it is possible to measure each of the base currents in a random order. Reconnect the lead to pin 1 to produce the full display.

    It is optional to sketch the set of curves, together with the calibration on the V_C axis and the current rating for each curve.

CONCLUSIONS

We have learned from this experiment that:

1. Varying the base voltage varies the base current.

2. Varying the base current, I_B, varies the collector current, I_C, which, in turn, varies the collector voltage, V_{CE}.

3. When I_B is fixed, varying V_{CC} changes I_C only slightly until V_{CC} drops below 0.5 volts.

4. The plot of I_C versus V_{CE} for a fixed base bias current, is called the collector characteristic curve.

5. The collector characteristic curves for various values of I_B are plotted on one graph and this is known as a Family of Characteristic Curves.

6. The collector curves may be used to help understand the operation of a transistor amplifier.

7. When a load line is plotted on the collector curves it allows us to select the optimum operating point also called the quiescent point or Q point.

8. The collector curves may be used to determine the transistor's dc beta and ac beta values.

9. Dc beta is calculated from:

$$\beta_{dc} = \frac{I_C}{I_B}$$

10. The value of the dc beta will vary depending upon where on the family of curves the calculation is made. The higher I_C, the higher the beta.

11. The value of the ac beta can be measured from the characteristic curves and is equal to:

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}$$

12. The collector curves may be displayed on an oscilloscope when V_{CC} is swept with an ac voltage and X-Y scope operation is used.

13. The load line can be displayed on an oscilloscope screen using X-Y scope operation and a varying input base current.

KEY TERMS

1. AC BETA, β_{ac}

   The ratio of the change in collector current to the corresponding change in base current, expressed as

   $$\beta_{ac} = \Delta I_C / \Delta I_B$$

2. BETA, β

   The current gain of a transistor wired in the common emitter configuration.

3. COLLECTOR CHARACTERISTIC CURVE

   A plot of the transistor output characteristic, V_{CE} versus I_C, for a constant value of I_B.

4. DC BETA, β_{dc}

   The ratio of the dc collector current to the dc base current, expressed as

   $$\beta_{dc} = I_C / I_B$$

5. FAMILY OF CURVES

   A set of collector curves for various values of I_B, all plotted on a single graph.

6. INPUT CURVE

   A plot of voltage, V_{BE}, versus current, I_B, for the base-emitter input circuit of the transistor.

7. LOAD LINE

   A graph of V_{CE} versus I_C for a given value of R_C that results in a straight line plot where one intercept point equals V_{CC} and the other, V_{CC}/R_C.

8. OPERATING POINT

   Also called the Q point, it is the value of I_C and V_{CE} with no input signal, when I_C and V_{CE} are at rest. The operating point is set by I_B.

ASSIGNMENT

Answer the following multiple choice questions.

1. In the CE configuration, the input is connected to the_____ and the output is taken from the _____.

   a. base; emitter.
   b. emitter; collector.
   c. base; collector.
   d. collector; base.

2. The input curve of a CE amplifier is a plot of:

   a. V_{BE} vs I_B.
   b. I_B vs I_C.
   c. V_{CE} vs V_{BE}.
   d. V_{CE} vs I_C.

3. The output curve of a CE amplifier is a plot of:

   a. V_{BE} vs I_B.
   b. I_B vs I_C.
   c. V_{CE} vs V_{BE}.
   d. V_{CE} vs I_C.

4. A set of output or collector characteristic curves can be used to determine:

   a. ac beta.
   b. dc beta.
   c. optimum operating point.
   d. all of the above.

5. In the CE configuration, as V_{CE} is reduced, I_C:

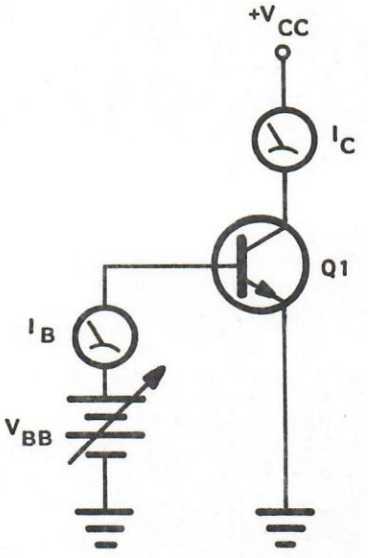
   a. reduces proportionately.
   b. drops suddenly below 1 volt of V_{CE}.
   c. increases gradually.
   d. none of the above.

6. The ac beta of a transistor is determined from:

   a. $\Delta I_B / \Delta I_C$.
   b. I_C / I_B.
   c. $\Delta I_C / \Delta I_B$.
   d. none of the above.

7. The value of the dc beta:

   a. increases with I_C.
   b. is constant with I_C variations.
   c. is equal to the ac beta.
   d. none of the above.



I_B	I_C
30 μA	5 mA
20 μA	2.8 mA

Figure 8 above refers to questions 8 and 9.

8. For the reading shown in the chart in Figure 8, the dc beta for transistor Q1 is:

   a. 166.
   b. 140.
   c. 50.
   d. either a or b.

9. For the readings shown in the chart in Figure 8, the ac beta for transistor Q1 is:

   a. 220.
   b. 166.
   c. 144.
   d. none of the above.

10. A load line is to be plotted for a CE amplifier with a V_{CC} of 20 volts and an R_C of 2 K. The X and Y intercept points are:

    a. X = 10 mA; Y = 20 V.
    b. X = 10 mA; Y = 10 V.
    c. X = 20 V; Y = 10 mA.
    d. none of the above.

Common Collector (CC) Amplifier Circuits

Lesson No. 9

SCOPE

1. This lesson is a reference for Unit J1, Experiment No. 9, Common Collector (CC) Amplifier Operation.

2. The Common Collector Amplifier has the input at the Base and the output at the Emitter of the Transistor.

3. The common collector circuit (CC) is also called an Emitter Follower (EF) and its major characteristics are a high input impedance, a low output impedance, no phase shift and a voltage gain of approximately 1.

4. The CC amplifier is ideal for amplifying signals from sources that have a high value of source resistance, R_S. The CC is also ideal for driving very low value load resistances (R_L) or low impedance loads.

5. To increase the CC input resistance, two CC amplifiers are connected together to form what is called a Darlington Amplifier circuit.

DISCUSSION

In all the common emitter experiments up to now, it was shown that the input is made to the base-emitter circuit and the output is taken from the collector-emitter circuit. It is also possible to use different combinations for the input and output circuits resulting in different circuit configurations. These circuit configurations are:

1. Common Emitter (CE); base-input and collector-output

2. Common Collector (CC); base-input and emitter-output

3. Common Base (CB); emitter-input and collector-output

Experiments 2 to 7 covered the following areas of the common emitter configuration:

a. Operating Regions
b. Current Gain
c. Voltage Gain
d. Bias Circuits
e. Emitter Resistor Degeneration
f. Voltage Divider Bias with bypassed and unbypassed emitter resistors
g. Input and Output Impedances

All of the concepts of bias, gain, stability, impedance, distortion or clipping, etc., from the CE experiments apply to the CC and CB circuits as well. This lesson and its associated experiment covers the Common Collector (CC) circuit and the next lesson and experiment cover the Common Base (CB) circuit.

COMMON COLLECTOR CIRCUIT

In the previous experiments, it was shown that the voltage gain of a common emitter amplifier stage decreased drastically if the input voltage generator had a large source resistance, R_S, and the amplifier input impedance, Z_{in}, was low. Ideally, Z_{in} of the amplifier stage should be very much greater than the resistance, R_S, of the voltage source for maximum signal input. The output voltage also decreased when the output load resistance, R_L, was low. Ideally, the amplifier should have a low output impedance.

The transistor configuration which has a very high input impedance and a very low output impedance is the COMMON COLLECTOR (CC) circuit shown in Figure 1.

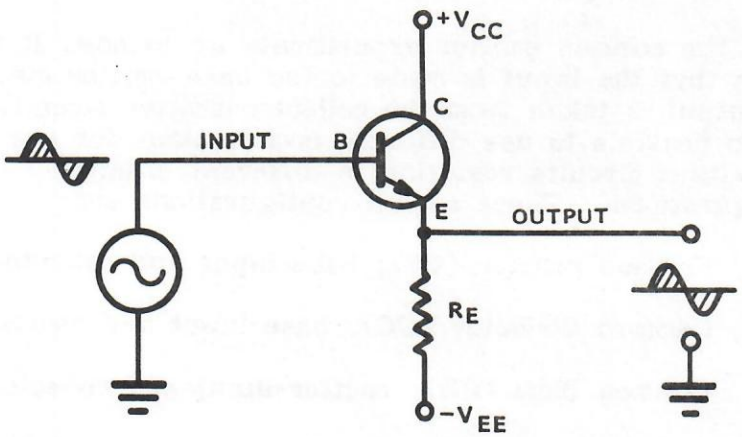


Figure 1 - Basic common collector amplifier circuit.

The input signal in Figure 1 is applied to the base and the output signal is taken from the emitter. The collector is at ac ground potential and is, therefore, common to both the input and output circuits, thus the name Common Collector. The phase of the output signal is the same as the input signal phase in the CC amplifier. The output voltage at the emitter equals the input voltage at the base differing only by the base-emitter diode voltage drop. The voltage gain is therefore approximately 1 or unity. This small voltage loss is called ATTENUATION.

The input impedance for the circuit of Figure 1 is given by the same equation used before for the CE amplifier and is:

$$Z_{in} = \beta(R_E) \qquad (1)$$

where R_E is the emitter load resistance. R_E is not bypassed in the CC and is high, typically 1 K. Therefore Z_{in} can be very high. For β = 200, Z_{in} would then be 200 K. Z_{in} becomes lower when an external load is connected to the output at the emitter.

The output impedance of the circuit of Figure 1 is very low so that it can drive any load. The output impedance of the CC circuit can be derived from the transistor model and shown to be given by the equation:

$$Z_{out} = r'e + \frac{R_S}{\beta} \qquad (2)$$

where R_S is the input source resistance and r'e is the base-emitter resistance referred to in earlier experiments.

Although it may seem that there is little value to an amplifier with a voltage gain of 1, the CC circuit is useful when a voltage amplifier with a high gain and a high value R_C (high Z_{out}), must drive a low resistance load such as a loudspeaker or even a motor. Thus, if we want an amplifier with a voltage gain of 50 to drive a load of 10 ohms or 100 ohms, we could use two transistor circuits; one a CE circuit for the voltage gain, connected to a CC circuit to drive the low value load resistance. This is usually done in audio power amplifier circuits.

As an example, in a CC amplifier, if R_E = 100 ohms, R_S = 10 K, beta = 200 and r'e = 25 ohms, then:

$$Z_{in} = \beta(R_E + r'e) = (200)\ (125)$$

$$\boxed{Z_{in} = 25\ K} \quad \text{HIGH}$$

$$Z_{out} = r'e + \frac{R_S}{\beta} = 25 + \frac{10{,}000}{200} = 25 + 50$$

$$\boxed{Z_{out} = 75\ \Omega} \quad \text{LOW}$$

The output signal voltage of the common collector amplifier is approximately equal to the input signal voltage and is in phase with the input. Thus, the output at the emitter "follows" the input at the base and, as a result, the CC stage is also called an EMITTER FOLLOWER (EF).

DARLINGTON AMPLIFIER

As explained above, the input resistance of a common collector amplifier, as seen by the signal source, is determined by $\beta(R_E)$. To increase R_{in} or Z_{in}, it is necessary to increase beta which can effectively be done by using the DARLINGTON PAIR, shown in Figure 2, which is simply two CC amplifiers connected together.

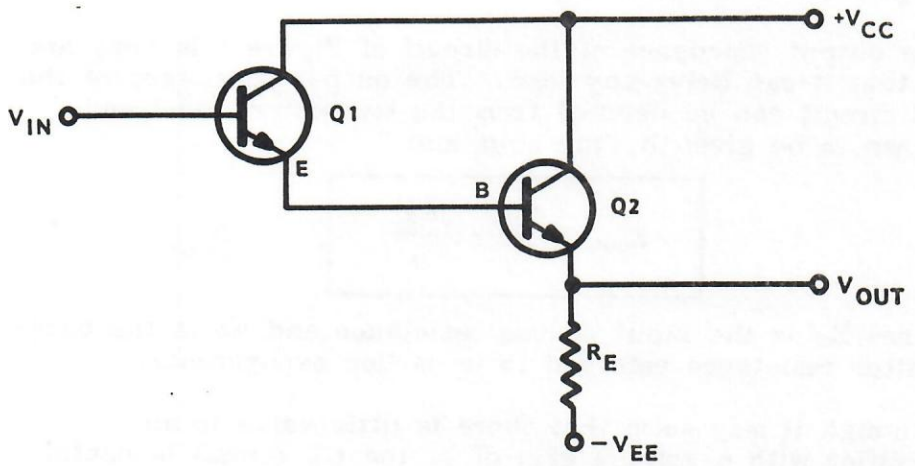


Figure 2 - Circuit of a Darlington amplifier.

As shown in Figure 2, the emitter current of Q1 drives the base of Q2. This produces a beta multiplication that results in a total of β of Q1 times β of Q2. As a result:

$$\boxed{\text{Darlington CC } Z_{in} = (\beta)(\beta)R_E} \qquad (3)$$

while for a single CC, we have

$$\text{Single CC } Z_{in} = \beta(R_E)$$

Given an R_E of 100 ohms and a beta of 200 for each transistor, we have:

$$\text{CC } Z_{in} = \beta(R_E)$$

$$= (200)\ 100 = \underline{20\ K}$$

$$\text{Darlington } Z_{in} = (\beta)(\beta)(R_E)$$

$$= (200)(200)\ 100 = \underline{4\ \text{Megohms}}$$

Some transistor manufacturers have placed a darlington pair in a single case, bringing out only three leads, base (1), emitter (2) and common lead from both collectors (3). The darlington pair case appears the same as a single transistor.

In the accompanying experiment we will demonstrate how the CC or EF circuit and the darlington pair circuit operate to maintain a voltage output across a low value load resistance. We will also measure Z_{in} and Z_{out} and compare the results to those obtained for the CE circuit.

VOLTAGE DIVIDER BIASED EF CIRCUIT

When both positive and negative voltage power sources are not available in the same circuit, it is necessary to use a voltage divider bias circuit for the emitter follower as shown in Figure 3.

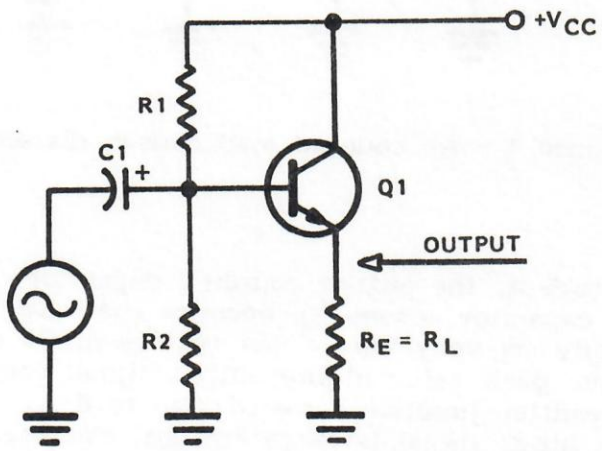


Figure 3 - Voltage divider biased common collector amplifier.

The behavior of the voltage divider biased emitter follower amplifier shown in Figure 3 is the same as that shown earlier in Figure 1 except that the input impedance, Z_{in}, is lower due to the parallel effect of R1 and R2. Thus:

VOLTAGE DIVIDER CC INPUT IMPEDANCE	$Z_{in} = R1//R2//(\beta R_E)$

(4)

Compare equation (4) above to equation (1) used to determine the input impedance for the circuit of Figure 1 and it will be apparent that, for a given transistor and R_E load value, Z_{in} will be less for the circuit of Figure 3.

Still another disadvantage of the circuit of Figure 3 occurs when the load to be driven cannot tolerate a direct current flow. When such a load is driven, it must be capacitively coupled as shown in Figure 4 and this often results in a distorted output.

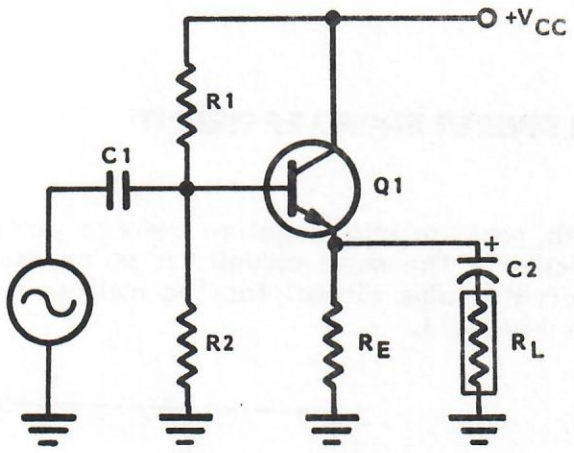


Figure 4 - Ac coupled load causes distorted output.

In Figure 4, the output coupling capacitor, C2, acts as filter capacitor across R_E because the value of R_L, typically, is very low. This results in C2 charging to the positive peak value of the output signal causing the base-emitter junction forward bias to drop to zero volts. If the input signal is large enough, the base-emitter junction may actually become reverse biased. Because of this, only the positive output peaks will appear across the load unless the input signal is kept to a very moderate level. For this reason the load driven by the CE circuit is most often directly coupled. When the load to be driven must be capacitively coupled, the output circuit will be designed to allow the coupling capacitor to discharge each half cycle after charging as will be shown in a later experiment.

POWER GAIN

While the common collector circuit produces no voltage gain, it does provide a power gain. The power gain, defined as A_p, is given as:

$$A_p = (A_i)(A_v) \tag{5a}$$

Because, in a CC amplifier, A_v is equal to 1 and A_i is approximately equal to β, then A_p can be shown as:

$$\boxed{A_p = \beta} \tag{5b}$$

KEY TERMS

1. ATTENUATION

   A decrease in the signal strength during its transmission from one point to another. A "gain" of less than "1."

2. COMMON COLLECTOR CIRCUIT (CC)

   A method of connecting a transistor into a circuit so that the input signal is applied to the base, the output signal is taken from the emitter and the collector is common to the input and output circuit (ac ground). It is also called an EMITTER FOLLOWER.

3. DARLINGTON AMPLIFIER

   Also called a Darlington Pair, it consists of two transistors with their collectors connected directly to the voltage source (V) and the emitter of Q1, connected to the base of Q2. The load is placed in the emitter of Q2. The circuit may be viewed as two common collector amplifiers.

4. DISTORTION

   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is often the result of operating a transistor amplifier in the non-linear region.

5. EMITTER FOLLOWER (EF)

Another name for the common collector circuit, so called because the output signal voltage at the emitter faithfully follows the input signal voltage at the base in both voltage variations and phase.

6. INPUT IMPEDANCE, Z_{in}

The impedance seen by a signal source looking into the input terminals of an amplifier. In the common collector, the input impedance equals $\beta(R_E)$.

7. OUTPUT IMPEDANCE, Z_{out}

The impedance measured at the output terminals of an amplifier when no load is connected. For the common collector, the output impedance is equal to $r'e + (R_S/\beta)$

8. POWER GAIN, A_p

The amount of power amplification achieved by a circuit. It is expressed as $A_p = A_v\ A_i$. In the common collector, the power gain is approximately equal to beta.

9. SOURCE RESISTANCE

The source resistance, R_S, also called the source impedance, is the internal resistance of a signal source that causes the signal voltage to drop when loaded.

ASSIGNMENT

Answer the following multiple choice questions.

1. The input resistance of a CC amplifier is:

   a. very low.
   b. the same as a CE.
   c. equal to $\beta(R_{in})$.
   d. none of the above.

2. The phase difference between the input and output signals of a CC amplifier is:

   a. 0°
   b. 90°
   c. 180°
   d. 270°

3. The output impedance of a CC amplifier is:

   a. very low.
   b. the same as a CE.
   c. equal to $\beta(R_E)$.
   d. none of the above.

4. A darlington amplifier circuit is most useful because its:

   a. output impedance is high.
   b. current gain is very low.
   c. voltage gain is very high.
   d. none of the above.

5. The darlington amplifier circuit is most useful when it is:

   a. being driven by a high impedance signal source.
   b. driving a high impedance load.
   c. being driven by a low impedance signal source.
   d. none of the above.

Common Collector (CC) Amplifier Operation

9

OBJECTIVES

When you finish this experiment you will be able to:

1. Measure the voltage gain and input and output impedances of a common collector (CC) amplifier.
2. Calculate the theoretical input and output impedances of a common collector amplifier.
3. Wire and test a Darlington Pair (CC) amplifier circuit.
4. Wire and test a Voltage Divider Biased ac coupled common collector amplifier.

REFERENCE

CES Lesson J1-9, Common Collector (CC) Amplifier Circuits

BACKGROUND

1. The CC amplifier, also called the emitter follower (EF) has a high input impedance, Z_{in}, equal to:

$$Z_{in} = \beta R_E$$

2. The CC amplifier has a low output impedance equal to:

$$Z_{out} = r'e + \frac{R_S}{\beta}$$

3. A "darlington pair" circuit uses two CC transistor circuits.
4. This experiment consists of seven parts.

   9.1 Voltage Source Loading
   9.2 Emitter Follower Loading
   9.3 Darlington Pair Loading
   9.4 Measurement of Z_{in}
   9.5 Measurement of Z_{out}
   9.6 Voltage Divider Biased CC Amplifier
   9.7 Troubleshooting (Optional)

PROCEDURE

9.1 VOLTAGE SOURCE LOADING

In this part of the experiment, we will demonstrate the voltage loss that occurs when a low resistance load is connected to a signal source with a high source resistance.

1. Wire the circuit shown in Figure 1.

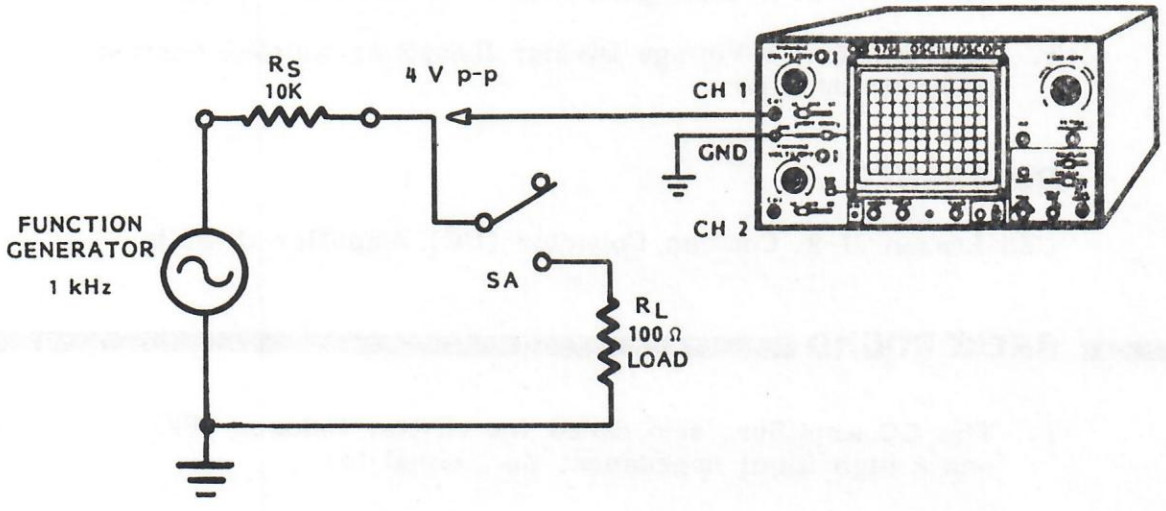


Figure 1 - Voltage loading circuit; EXPERIMENT.

The circuit in Figure 1 shows the Function Generator voltage source with a series 10 K source resistor, R_S. The load used in the test is a 100 ohm resistor placed in the circuit by switch SA.

With switch SA UP (open), set the sinewave input to 1 KHz at 4 volts p-p.

2. Connect the load by setting switch SA DOWN. Measure the reduced output voltage indicated on the oscilloscope and record it below.

DIRECT CONNECTION OUTPUT VOLTAGE AT THE LOAD	V_{out} = mV p-p

The expected output voltage is given by the voltage divider equation and should be:

$$V_{out} = V_{NL} \frac{R_L}{(R_S + R_L)} = (4) \frac{100}{(10{,}000 + 100)} \cong 0.04 \text{ V} = \underline{40 \text{ mV p-p}}$$

How does the above measurement for V_{out} compare to the expected results?

You may conclude from the above results that a low resistance load, R_L, connected across a signal voltage that has a high source resistance, R_S, will cause a severe drop in signal voltage level.

9.2 EMITTER FOLLOWER (CC) LOADING

In this part of the experiment, you will connect the low resistance load of 100 ohms to the same signal source through a Common Collector or Emitter Follower transistor circuit and you will observe how the loading on the signal source is reduced because the input resistance of the CC is high, equal to βR_E and R_E is the 100 ohm load.

3. Modify the circuit of Figure 1 by adding the common collector transistor amplifier circuit as shown in Figure 2. Be sure that the 100 ohm emitter resistor is connected to -V2 to provide the proper forward bias for the base-emitter junction.

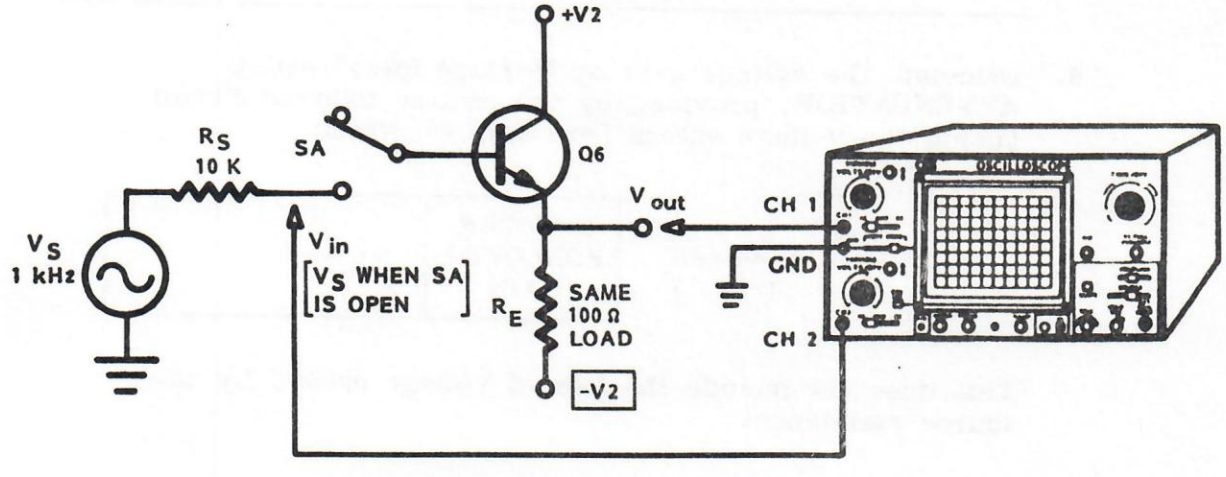


Figure 2 - Emitter follower circuit EXPERIMENT.

4—COMMON COLLECTOR (CC) AMPLIFIER OPERATION

4. With switch SA UP (open), check to see that the input source voltage, V_S, is still 4 volts p-p as indicated by the CH 2 display of the scope.

   Set switch SA DOWN and measure both V_{in} and V_{out} and record the voltages below.

INPUT VOLTAGE LOADED WITH CC	V_{in} = V p-p
OUTPUT VOLTAGE AT THE LOAD	V_{out} = V p-p

   Do we obtain a higher signal voltage across the 100 ohm load when the CC amplifier circuit is used as compared to the circuit in Figure 1?

   _____

   _____

   Does the input signal voltage at the transistor base drop when using the CC amplifier or does it remain at 4 volts p-p?

   _____

   _____

5. Compare the phase difference between the input and output signals displayed on the oscilloscope. What is their phase relationship?

   _____

   _____

6. Calculate the voltage gain or "voltage loss," called ATTENUATION, provided by the emitter follower circuit (using the voltage values from step 4), from:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{(\quad)}{(\quad)}$$

EMITTER FOLLOWER GAIN	A_v =

   This does not include the loss of voltage caused by the source resistance.

7. We can calculate the expected CC amplifier loading effects. Assuming a beta of 200 for the transistor, and the R_E of 100 ohms given in Figure 2, the input impedance, based on $\beta(R_E)$ is:

$$Z_{in} = (200)\ (100)$$

$$Z_{in} = \underline{20\ K}$$

The theoretical V_{in} or V_{out} based on a source voltage, V_S, of 4 volts and a source resistance, R_S, of 10 K is given by the standard voltage divider equation.

$$V_{in} = (V_S)\frac{Z_{in}}{(R_S + Z_{in})} = (4)\frac{20K}{(10\ K + 20\ K)} = \underline{2.6\ V\ p\text{-}p}$$

How does this calculated loaded input voltage compare to the measured input voltage you obtained in step 4?

_____

_____

_____

8. Note that the original 4 volt source has been reduced to 2.6 volts at the 100 ohm load resistor using the EF configuration. This is much better than the 40 millivolts which resulted when the 100 ohm resistor was connected across the source without a transistor.

You may conclude that the emitter follower circuit transforms its load resistance in the emitter so that is appears as beta times higher between the base to ground input terminals. This high input impedance reduces the loading effect on the voltage source. You have also observed that V_{out} approximately equals V_{in} and that there is no phase shift between V_{in} and V_{out}.

9.3 DARLINGTON PAIR (EF) CURCUIT LOADING

In this part of the experiment, you will construct a darlington pair circuit to increase the input impedance. This increased Z_{in} will be evidenced by less loading on the signal source and a consequent increased output voltage at the load.

9. Modify the circuit of Figure 2 or rewire it completely to result in the darlington circuit shown in Figure 3.

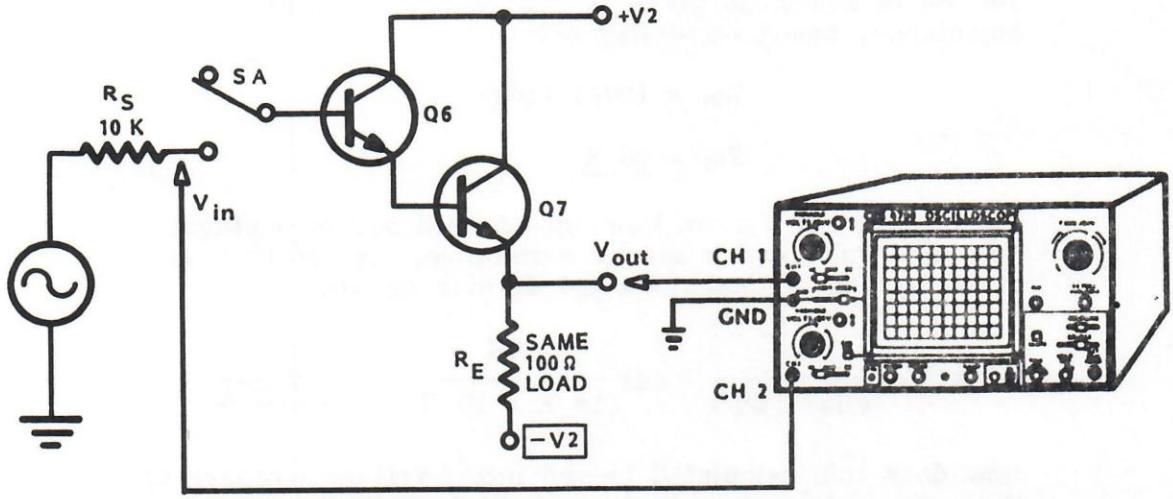


Figure 3 - Darlington pair emitter follower EXPERIMENT.

With switch SA UP (open), use the scope to set the input voltage at 4 volts p-p as before.

10. Set switch SA DOWN and measure the loaded input voltage and output voltages.

INPUT VOLTAGE LOADED BY THE DARLINGTON	V_{in} = V p-p
DARLINGTON CIRCUIT OUTPUT VOLTAGE AT THE LOAD	V_{out} = V p-p

How does the darlington output voltage compare to the output obtained when a single emitter follower stage was used in step 4?

The difference in output voltage between step 4 and step 10 above is due to the much higher input impedance of the darlington causing reduced loading effects.

11. What is the darlington stage gain or attenuation?

$$A_v = \frac{V_{out}}{V_{in}} = \frac{(\quad)}{(\quad)}$$

DARLINGTON VOLTAGE GAIN	A_v =

We have seen that the darlington common collector (or emitter follower) circuit does not load the input source as much as the single transistor emitter follower. This results in a higher ac input signal voltage and thus a higher output signal voltage. The voltage attenuation, A_v, for the darlington is slightly greater than that for the single emitter follower because a loss is suffered across both base-emitter transistor junctions.

9.4 MEASUREMENT OF EMITTER FOLLOWER Z_{in}

In this part of the procedure, you will measure the ac input impedance as seen at the base of the transistor in the emitter follower circuit.

12. Wire the emitter follower circuit shown in Figure 4.

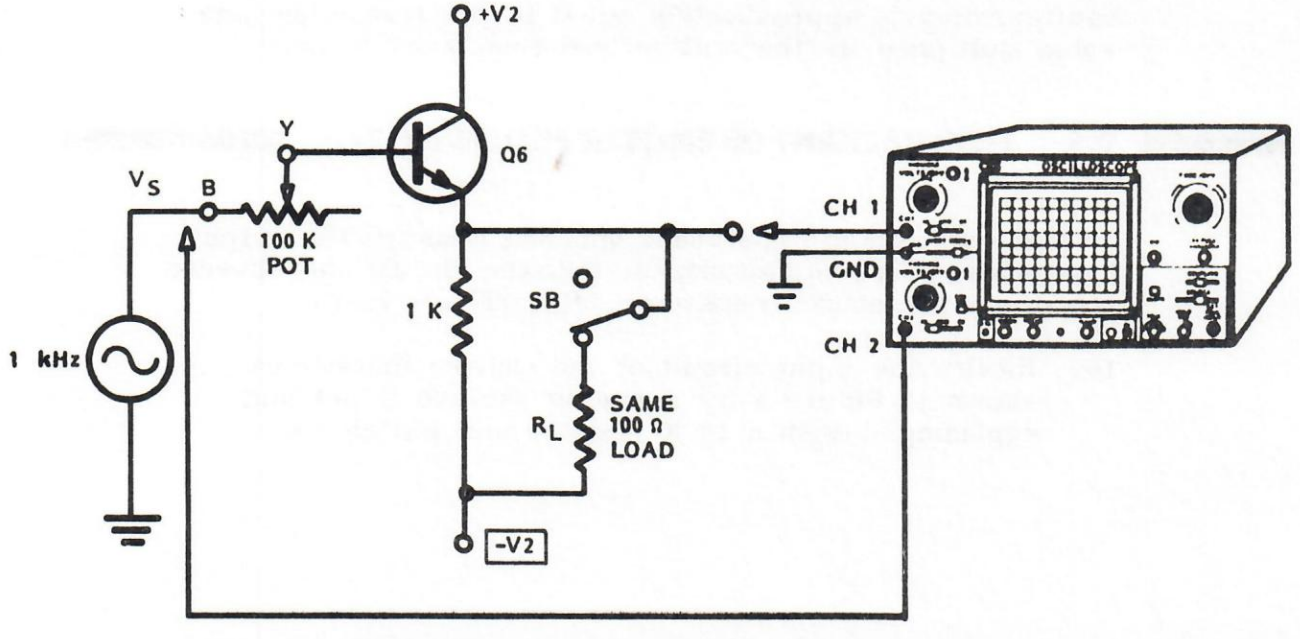


Figure 4 - Circuit set-up to measure Z_{in} ; EXPERIMENT.

13. Set the 100 K pot fully CCW (zero resistance) and place switch SB DOWN to connect the 100 ohm load to the circuit.

14. Adjust the ac input signal level for an output, V_{out}, of 4 volts p-p.

    Now rotate the 100 K pot CW until the output level drops in half to 2 volts p-p. The setting of the 100 K pot now equals Z_{in}.

15. Determine the resistance of the pot by counting the number of dial markings on the panel (each division equals 10 K) or measuring the actual resistance with an ohmmeter. Record the resistance below.

MEASURED EMITTER FOLLOWER Z_{in}	Z_{in} = K

How does the measured Z_{in} compare to the theoretical input impedance calculated in step 7, based on a beta of 200 where ($Z_{in} = \beta(R_E) = (200)(100) = 20$ K)?

9.5 MEASUREMENT OF EMITTER FOLLOWER Z_{out}

In this part of the experiment you will measure the output impedance, Z_{out}, of the emitter follower circuit and observe how the input source resistance, R_S, affects Z_{out}.

16. Rewire the input circuit of the emitter follower as shown in Figure 5 by removing the 100 K pot and replacing it with a 10 K resistor and switch SA.

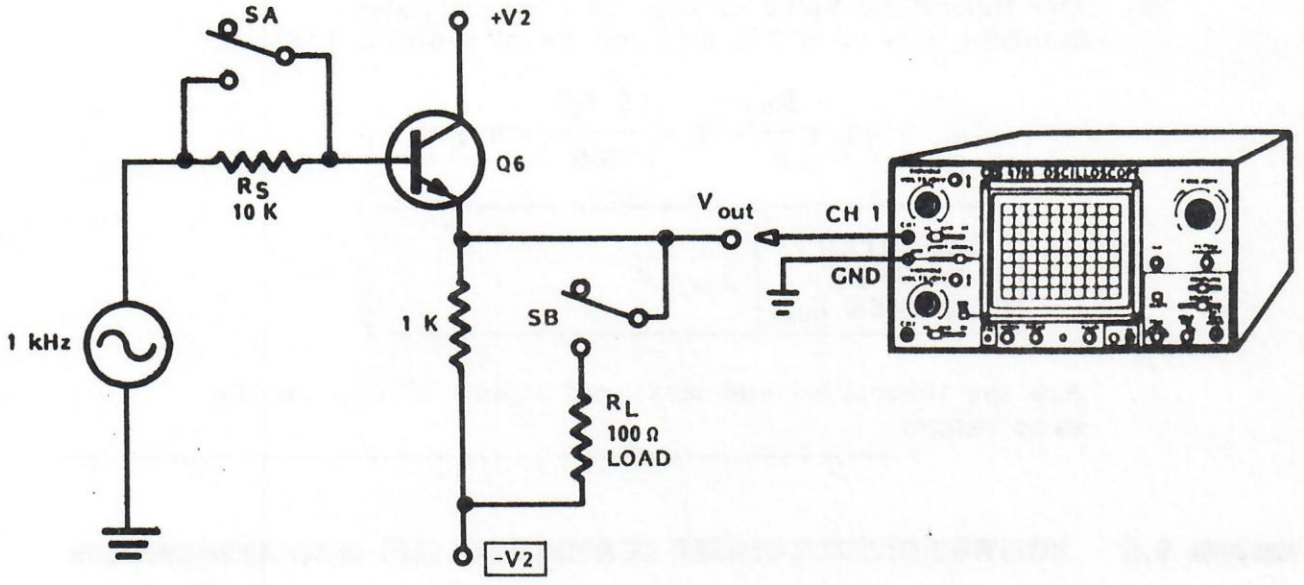


Figure 5 - Circuit set-up to measure Z_{out} ; EXPERIMENT.

17. Place switches SA and SB UP to result in no load and a 10 K value of R_S.

    Adjust the input signal level for a 4 volt p-p output, V_{out}, on CH 1. This represents the NO LOAD output voltage.

UNLOADED V_{out}	V_{NL} = V p-p

18. Place switch SB DOWN to connect the 100 ohm load, R_L, in the circuit. The output voltage will be reduced. Measure and record the loaded output voltage.

100 OHM LOADED V_{out}	V_L = V p-p

19. Calculate Z_{out} from the equation below, which is derived from the voltage divider equation.

$$Z_{out} = R_L \frac{(V_{NL} - V_L)}{V_L} = 100 \frac{4 - (\quad)}{(\quad)}$$

MEASURED EMITTER FOLLOWER Z_{out}	Z_{out} =

20. The theoretical value of Z_{out} can be calculated, assuming a beta of 200 and and r'e of 8 ohms, from:

$$Z_{out} = r'e + \frac{R_S}{\beta} = 8 + \frac{10{,}000}{200} = 8 + 50$$

EXPECTED EMITTER FOLLOWER Z_{out}	Z_{out} =

Are the theoretical and measured values of Z_{out} in the same range?

9.6 VOLTAGE DIVIDER BIASED CC AMPLIFIER (EF)

In this part of the experiment you will wire and test an ac coupled voltage divider biased emitter follower circuit that can be used when dual positive and negative power supplies are not available. The voltage divider bias circuit results in a lower input impedance due to the paralleling effects of the two voltage divider resistances. An ac coupling capacitor is required in order to prevent upsetting the dc base bias as explained earlier in the CE amplifier experiments.

21. Wire the ac coupled emitter follower circuit shown in Figure 6.

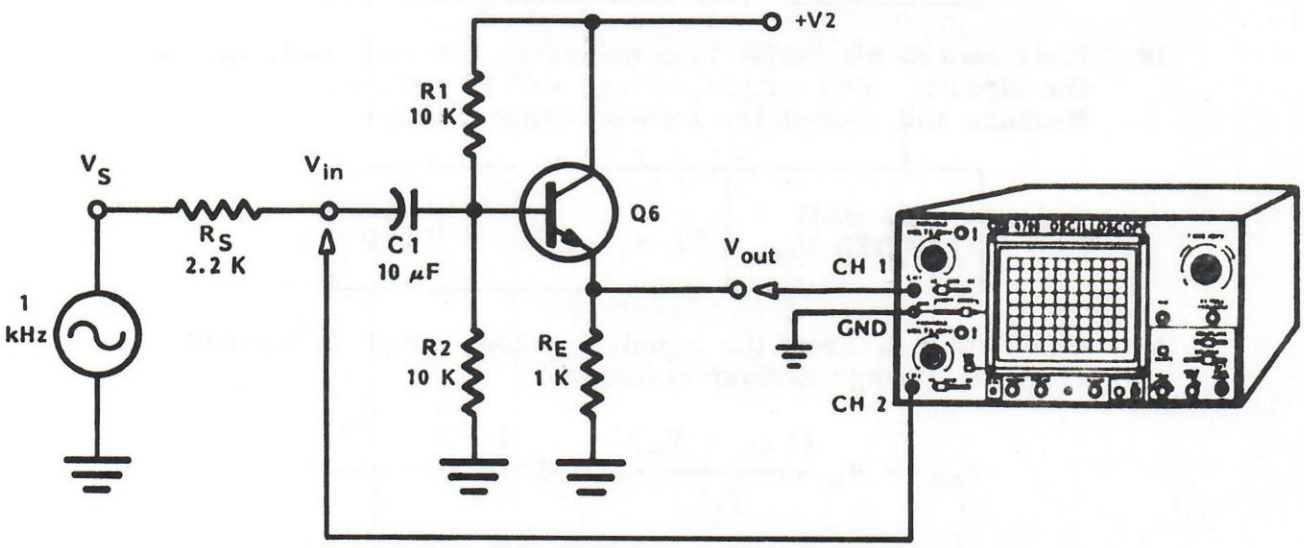


Figure 6 - Ac coupled, voltage divider biased, single power source emitter follower EXPERIMENT.

22. Set the input signal level at 8 volts p-p as indicated on the CH 2 display.

    Observe the resulting output signal and determine if any distortion is present.

    _____

23. Increase the input signal level to maximum. What is the effect on the output?

    _____

    _____

    _____

24. Add a capacitively coupled load to the circuit of Figure 6 as shown in Figure 7 and add the two meters. If a second meter is not available, reconnect the panel meter to read the base-emitter voltage as necessary.

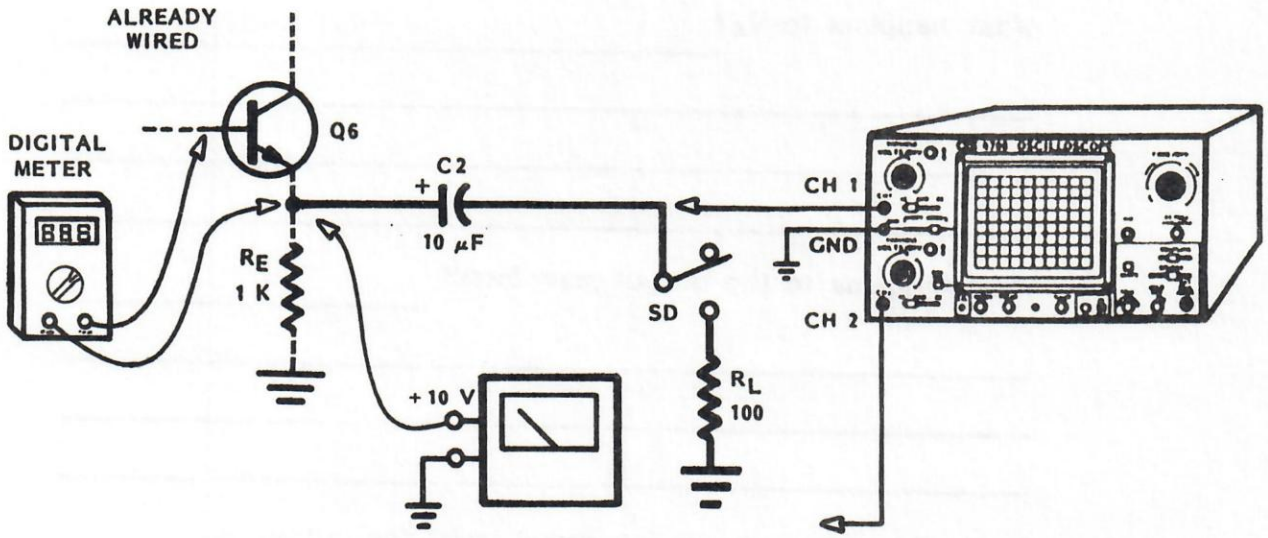


Figure 7 - Addition of output coupling capacitor; EXPERIMENT.

25. Place switch SD in the UP position so the R_L, 100 ohms, is not connected.

    Set V_{in} to 8 volts p-p and observe that the output signal is still the same amplitude and undistorted.

26. Reduce the input signal level to zero by rotating the Sine Ampl. control fully CCW.

Measure and record V_E and V_{BE}. If the digital meter is not available use the panel meter for both readings.

V_E = V	V_{BE} = V

27. Place switch SD DOWN and observe that V_E and V_{BE} do not change value. Now slowly increase V_{in} while observing V_E, V_{BE} and the output waveform displayed on CH 1.

What happens to V_{BE}? _____

What happens to V_E? _____

What happens to the output waveform? _____

28. Gradually reduce the input signal until the output is no longer distorted. What is the maximum allowable input signal before distortion occurs? _____

You may conclude from the above that an emitter follower amplifier can be designed to operate from a single power source if a voltage divider bias circuit is used. This circuit will have a lower input impedance than the emitter follower that uses two voltage sources. This is due to the paralleling effect of R1 and R2 in Figure 6. While the input impedance of the circuit of Figure 6 is lower than Z_{in} of Figure 1, it may still be equal to or greater than Z_{in} of a CE configuration when R_E is bypassed.

9.7 TROUBLESHOOTING (OPTIONAL)

In this part of the experiment, you will insert faults (opens and shorts) into the circuit and observe their effects on the dc bias voltages and the ac output signal. We will use the same circuit as in Figure 6.

29. Set the ac input signal level for a 2 volt p-p output.

    Measure the dc transistor B, E and C voltages with respect to ground and record the readings in line 1 of Table 1, No Fault.

NO.	FAULT	EFFECT ON VOLTAGES			
		V_B	V_E	V_C	AC EMITTER OUTPUT
1	No Fault				Normal
2	Shorted B-E				
3	Shorted C-E				
4	Shorted C1				
5	Shorted R_E				
6	Open R_E				
7	Open R1				
8	Open R2				
9	Open Collector*				

*Measure collector voltage from loose end of removed wire lead because this is how an open collector is simulated.

TABLE 1 - Data for faults in the circuit of Figure 6.

30. Insert the faults in the circuit of Figure 6, as listed in Table 1, by adding a wire lead to the panel to introduce a short or by removing a wire from the panel to introduce an open circuit. For each fault, record the effect on the output waveform. Then measure and record the base emitter and collector voltages with respect to ground.

CONCLUSIONS

We have learned from the experiment that:

1. The emitter follower has a high input impedance and a low output impedance.

2. The emitter follower amplifier transforms a given value of emitter load resistance to a higher value of base input resistance, equal to $\beta(R_E)$.

3. The emitter follower's high input impedance will not severely load a voltage source that has a high R_S value.

4. The emitter follower, because of its low output impedance, can drive low resistance loads.

5. The emitter follower has a voltage gain of slightly less than 1.

6. The emitter follower introduces no phase shift or inversion between the input an output signals as does the CE amplifier.

7. The emitter follower's output impedance, Z_{out}, is low and is equal to $r'e + (R_S/\beta)$.

8. Two emitter followers, in a darlington pair circuit, provide an even higher input impedance.

9. In the voltage divider biased emitter follower, the input impedance is reduced due to the two voltage divider resistors in parallel with R_{in} at the base.

KEY TERMS

1. ATTENUATION

   A decrease in the signal strength during its transmission from one point to another. A gain of less than "1."

2. COMMON COLLECTOR CIRCUIT (CC)

   A method of connecting a transistor into a circuit so that the input signal is applied to the base, the output signal is taken from the emitter and the collector is common to the input and output circuit (ac ground).

3. DARLINGTON AMPLIFIER

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   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is often the result of operating a transistor amplifier in the non-linear region.

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   Another name for the common collector circuit so called because the output signal at the emitter faithfully follows the input signal at the base in voltage variations and phase.

6. INPUT IMPEDANCE, Z_{in}

   The impedance seen by a signal source looking into the input terminals of an amplifier. In the common collector, the input impedance equals $\beta(R_E)$.

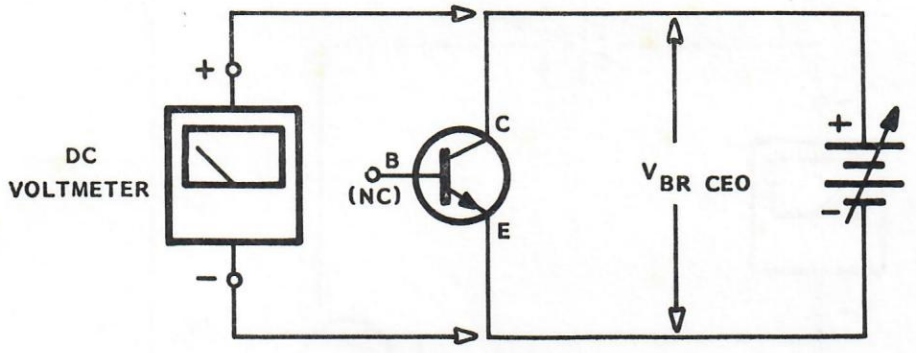

Figure 3 - Breakdown test for $V_{BR\ CEO}$.

Leakage Currents: Transistor leakage current ratings also use the three letter subscript system. There are three leakage current ratings with several variations as shown in Table 3.

RATING	DESCRIPTION
I_{CBO}	Collector Leakage Current: Also called the collector cut-off current, it is the dc collector current with the collector-base junction reverse biased with the emitter floating. It is also called I_{CO}.
I_{CEO}	Collector Leakage Current: Also called the collector cut-off current, it is the dc collector current flow from emitter to collector with the base open.
I_{EBO}	Emitter Leakage Current: Also called the emitter cut-off current, it is the dc emitter current flow with the emitter-base junction reverse biased and the collector floating. It is also called I_{EO}.

TABLE 3 - Transistor current leakage ratings.

The method of measuring I_{CBO} is shown in Figure 4. Note that the B-C junction is reverse biased, which is normal, and the microammeter is measuring the leakage current flow. Note also that the emitter is floating. Other leakage currents are similarly measured with the junctions reverse biased.

ASSIGNMENT

Answer the following multiple choice questions.

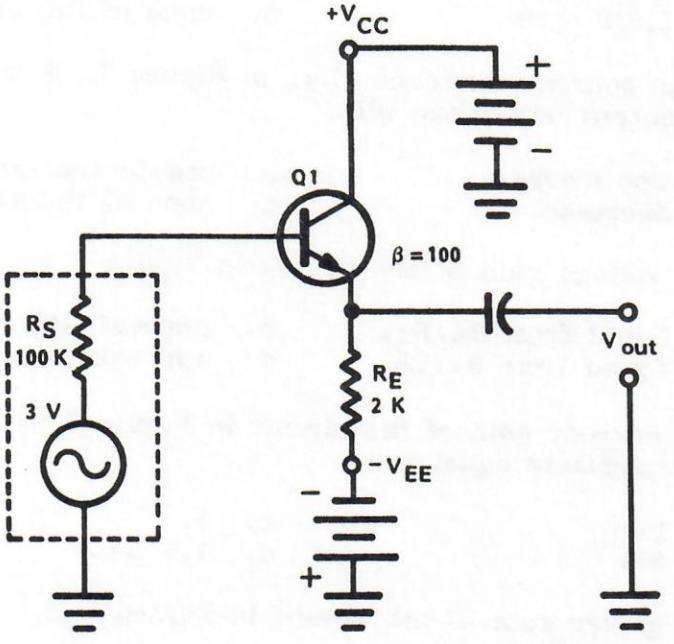

Figure 7 above refers to questions 1 to 8.

1. The amplifier circuit shown in Figure 7 is called a (an):

   a. common emitter.
   b. emitter follower.
   c. common collector.
   d. either b or c.

2. The input impedance at the base of Q1 in Figure 7 is approximately:

   a. 100 K.
   b. 100 ohms.
   c. 200 K.
   d. 2000 ohms.

3. The measured input signal voltage at the base of Q1 in Figure 7 will be:

   a. 3 volts.
   b. 2 volts.
   c. 1 volt.
   d. 0 volts.

The collector to emitter saturation voltage, $V_{CE\ sat}$, is much lower than the diode forward voltage drop because the two opposite polarity voltage drops, NP (collector to base) and PN (base to emitter) are now series opposing and partially cancel each other.

CURRENT GAIN AND NOISE

In addition to the first five transistor characteristics, listed in Table 1, that are common to the diode (with some variations), there are two additional transistor characteristics shown that have no diode equivalent. The first is CURRENT AMPLIFICATION, identified as alpha, beta, h_{fe} h_{fb}, or h_{fc}, depending upon the configuration. The second addition is the NOISE FIGURE, NF which refers to the unwanted noise generated in the transistor during the process of amplification and measured as the ratio of the output noise to input noise.

TEMPERATURE EFFECTS

All the characteristics listed in the transistor specification sheets are based on an operating temperature of 25°C (77°F) which is considered to be "room temperature." If a transistor is operated at a temperature above 25°C all the specifications change. The transistor's allowable power dissipation, P_D, must be reduced or DERATED. Also, the leakage currents will increase with temperature. Because the specification sheets give the "Maximum Allowable Ratings," the figures should not be exceeded. In fact, the circuits should be designed so that the transistors operate well below the maximum ratings to provide a safety margin to reduce the possibility that the transistors might eventually fail in use.

Thus, if we expect the equipment to operate at 65°C (140°F) then the increase in temperature, in centigrade, is 65 - 25 = 40°C. The 2N3903 and 2N3904 are both rated for a dissipation of 625 mW at 25°C. For operation at 65°C, they would both have to be derated at 5 mW/°C to:

POWER DISSIPATION AT 65°C (140°F)

$$P_{D\ max} = 625\ mW - \left[\frac{5mW}{°C} \times 40°C \right]$$

MAX. POWER DISSIPATION AT 65°C	$P_{D\ max} = 425\ mW$

9. The input impedance seen by a generator connected to V_{in} in Figure 8, will be approximately:

   a. 200 K.
   b. 75 K.
   c. 37.5 K.
   d. 31.5 K.

10. In the circuit of Figure 8, if you wish to maintain a high input impedance it is done by:

   a. keeping resistors R1 and R2 as high as possible.
   b. making R3 as high as possible.
   c. using a transistor with the highest possible beta.
   d. all of the above.

11. The output impedance of the circuit in Figure 8, given a source resistance of 30 K and a load resistance of 1 K, is closest to:

   a. 1 K//1 K = 500 ohms.
   b. 150 ohms.
   c. 75 K//75K = 37.5 K.
   d. 300 ohms.

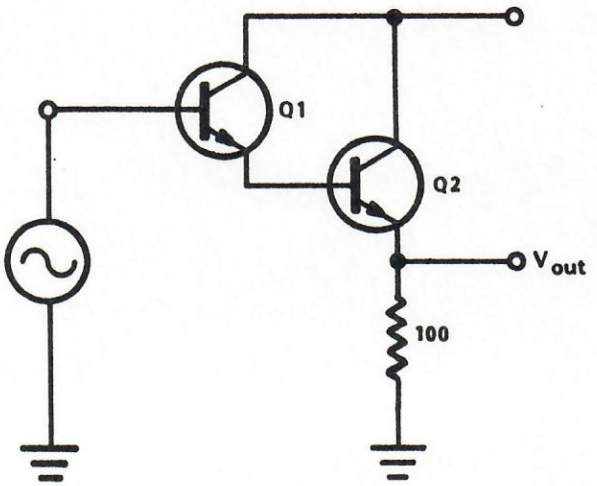

Figure 9 above refers to questions 12 to 15.

12. The circuit shown in Figure 9 is called a:

   a. Cascaded Emitter Follower (CEF).
   b. Compound Common Collector (CCC).
   c. Darlington Pair Amplifier.
   d. Common Emitter Follower.

The information provided in a transistor specification sheet falls into seven categories. Five of these categories were covered when diodes were studied and apply equally to transistors since the simplest transistor model consists of two back-to-back diodes (Experiment J1-1). A general listing of these areas is given in Table 1 and, within each area are listed the several variations for transistors. These variations occur because the transistor is a three terminal device and thus there are more leakage paths and voltage breakdown possibilities.

CHARACTERISTIC	DIODE	TRANSISTOR
MAXIMUM POWER OR CURRENT	P - Continuous power dissipation I_F - Maximum forward current	P_D - Maximum power dissipation $I_{C\ max}$ - Maximum allowable collect current
LEAKAGE CURRENT	I_{REV} - Reverse current	I_{cbo} , I_{eco} , I_{ebo} - Leakage currents between E, B and C.
BREAKDOWN VOLTAGE (Reverse biased junctions)	PIV - Peak inverse voltage	$V_{BR\ CBO}$, $V_{BR\ CEO}$, $V_{BR\ EBO}$ - Maximum reverse bias breakdown (BR) voltage
CONDUCTIVITY	V_F - Forward biased junction voltage drop	$V_{CE\ sat}$ - Saturation collector to emitter voltage drop
FREQUENCY RESPONSE	t_{rr} - Reverse recovery time	t_{on} , t_{off} - Delay times f_t - Frequency for unity gain
AMPLIFICATION	Not Applicable	α, β, h_{fb} , h_{fe} , h_{fc} - Current gains
NOISE	Not Applicable	NF - Ratio relating output to input noise

TABLE 1 - Diode and transistor data comparison.

Common Base (CB) Amplifier Circuits

Lesson No. 10

SCOPE

1. This lesson supports Unit J1-Experiment No. 10, Common Base (CB) Amplifier Operation.

2. The common base amplifier has the input signal applied to the emitter and the output signal taken from the collector. The circuit configuration is described together with the equations for voltage gain, current gain, power gain and input and output impedances.

3. This is the last of the three configurations discussed and therefore a summary of characteristics for all three configurations, CE, CC and CB is presented in table form.

DISCUSSION

The previous experiments described the operation of the common emitter (CE) and common collector (CC) amplifiers. We will now examine the circuit, operation and characteristics of the third configuration, the COMMON BASE (CB). The development of the conventional common base configuration is shown in Figure 1.

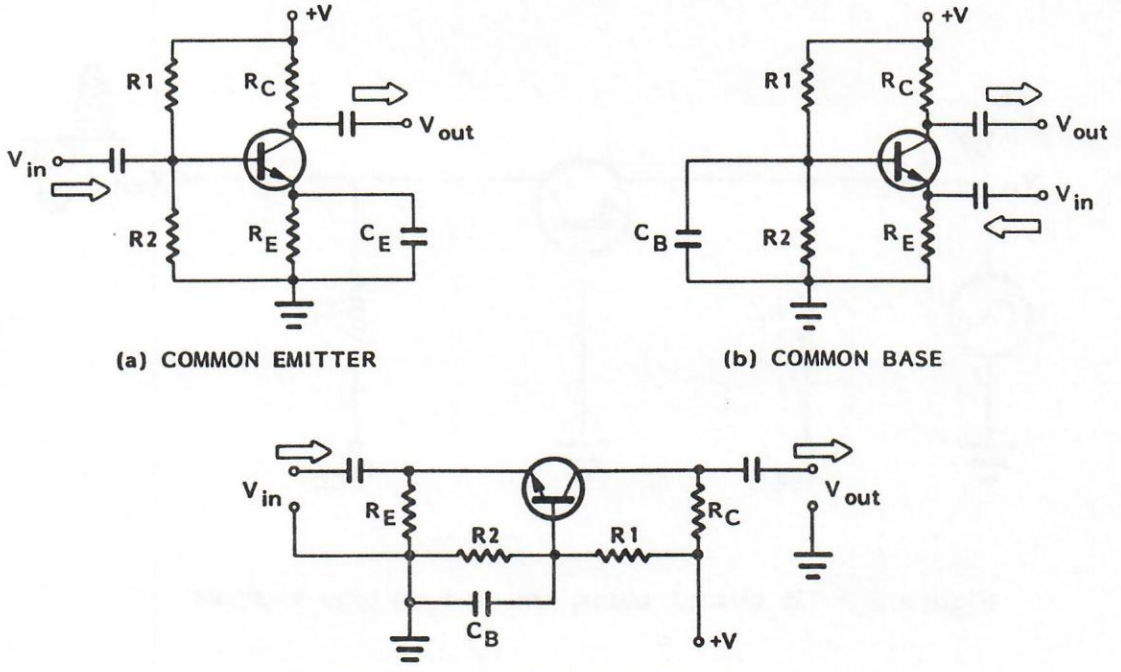

Figure 1 - Development of the common base circuit.

Transistor Specification Sheets

INFO SHEET 4

OBJECTIVES

When you finish this information sheet you will be able to:

1. Use a Transistor Specification Sheet to determine the characteristics of a transistor.
2. Define all the transistor breakdown voltage ratings.
3. Define all the transitor current leakage ratings.
4. Define all the transistor frequency rating forms.
5. Convert from one frequency rating to any other frequency rating form.

DISCUSSION

In all the previous experiments, the only transistor characteristic that was used was beta, the current gain. Even there, circuits were designed to be independent of beta so that all we had to know was the transistor type, NPN or PNP, to design the circuit and, on occasions, whether the transistor was germanium or silicon. The applied voltage was a maximum of 9 volts or 18 volts if the positive and negative voltages were both used. The maximum current that could be obtained was limited by the power supply. The frequencies that were amplified were in the range of 1 Hz to 100 kHz when supplied by the Function Generator or in the range of 1 MHz when used with radio signals. The trainer was designed so that the power source limits could not burn out the transistors.

MAXIMUM RATINGS

If we were to apply 100 volts to any transistor on the trainer, we would expect it to "burn out" and if we were to supply 20 amperes to the transistor we would expect a similar fate. Even if the voltage applied was 20 volts with a resulting 20 mA current, the power dissipated by the transistor would be 4 watts (20 x 200 mA) and a small, low power transistor would not survive. It becomes important, therefore, to know the maximum voltages, currents and power ratings associated with a transistor when designing or repairing equipment.

CB VOLTAGE GAIN

The voltage gain for the CB amplifier is the same as the CE amplifier and is:

$$A_v = \frac{R_C}{r'e} \qquad (1)$$

The stability of A_v is a function of the stability of r'e. We know from earlier experiments that r'e varies with temperature, the value of I_C and from transistor to transistor of the same type. As in the CE configuration, if it is necessary to stabilize A_v, a Swamping Resistor, R_D, may be added as shown in Figure 3, with the resulting loss in gain. Because this type of amplifier is usually used where the input signal levels are low, and maximum gain is desired, the swamping resistor is not frequently used.

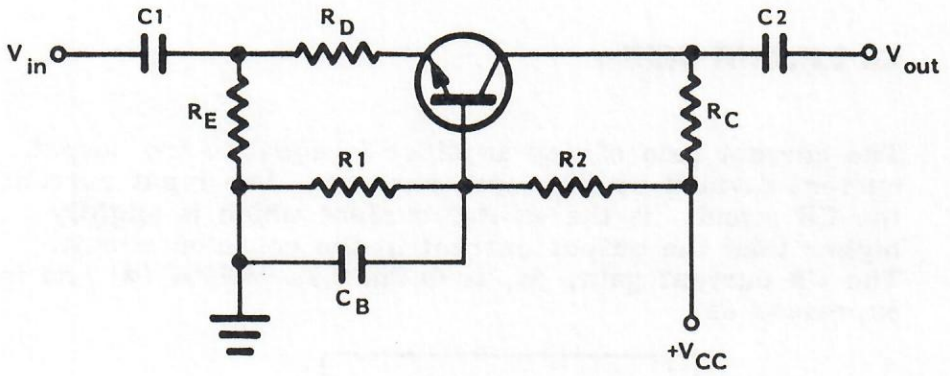

Figure 3 - CB configuration with a swamping resistor, R_D.

CB INPUT IMPEDANCE

The input impedance of the CB amplifier (without a swamping resistor), shown in Figure 1(c) is very low and given by:

$$Z_{in} = R_E // r'e \qquad (2)$$

Because the base is at ac ground, it can be seen that the base-emitter junction is in parallel with R_E (through capacitor C_B). Because r'e is so low ($25/I_E$), and the value of R_E is usually 1 K or more, the input impedance is expressed as:

$$Z_{in} = r'e \qquad (3)$$

6. In the CB configuration the:

   a. input impedance is considered to be very low.
   b. voltage gain is considered to be equal to that of the CE configuration.
   c. current gain is approximated as 1.
   d. all of the above.

7. Common base circuits are used where:

   a. low level high frequency signals are to be amplified.
   b. only low frequency high level signals are encountered.
   c. high current gain is needed.
   d. high power gain is necessary.

8. The current gain of the CB configuration is called _____ and is equal to _____.

   a. gamma; I_C/I_B
   b. beta; I_C/I_B
   c. alpha; I_C/I_E
   d. epsilon; I_E/I_C

9. The major disadvantage of CB amplifier is its:

   a. low voltage gain.
   b. low input impedance.
   c. high current gain.
   d. none of the above.

10. Draw the circuit of a common base amplifier that uses a single power source, a PNP transistor and is voltage divider biased.

AMPLIFIER CHARACTERISTIC SUMMARY

We have studied the basic characteristics of the three configurations, the common emitter, common collector and now, the common base. Recall that the COMMON EMITTER provides both a current gain and a voltage gain and so provides a very high power gain. For this reason the common emitter is the most widely used of the three circuits.

In comparison, the COMMON COLLECTOR produces a current gain approximately equal to beta but a voltage gain of slightly less than 1. The power gain is then approximately equal to beta. For this reason, this circuit is used as a current amplifier only for output power amplifier circuits.

The COMMON BASE configuration produces a high voltage gain, equal to the voltage gain of the common emitter amplifier. The current gain of the common base, however, is less than 1. The common base configuration has application in radio circuit voltage amplifiers that operate at very high radio frequencies and will be covered in later units.

Besides differing in voltage, current and power amplification characteristics, the three configurations also differ in input and output impedances and phase shift characteristics, Θ. All of these characteristics are summarized in Table 1 to allow quick comparisons.

CONFIG-URATION	CHARACTERISTICS					
	CURRENT GAIN A_i	VOLTAGE GAIN A_v	POWER GAIN A_p	INPUT IMPED-ANCE	OUTPUT IMPED-ANCE	PHASE SHIFT Θ
CE	HIGH $A_i = \frac{I_C}{I_B} \cong \beta$	HIGH $A_v = \frac{R_C}{r'e}$	VERY HIGH $A_p = A_i A_v = \beta(R_C/r'e)$	MEDIUM $Z_{in} = \beta r'e$	HIGH $Z_{out} = R_C$	180°
CC	HIGH $A_i = \frac{I_E}{I_B} \cong \beta$	LOW $A_v = \frac{R_E}{r'e + R_E} \cong 1$	MEDIUM $A_p = A_i \cong \beta$	HIGH $Z_{in} = \beta R_E$	LOW $Z_{out} = r'e + \frac{R_S}{\beta}$	0°
CB	LOW $A_i = \frac{I_C}{I_E} \cong 1 = \alpha$	HIGH $A_v = \frac{R_C}{r'e}$	HIGH $A_p \cong A_v = R_C/r'e$	VERY LOW $Z_{in} = r'e$	HIGH $Z_{out} = R_C$	0°

TABLE 1 - Comparision of CE, CC and CB characteristics.

KEY TERMS

1. ALPHA (α)

   Current gain of the common base configuration measured from emitter to collector. Alpha is slightly less than 1 but is approximated as 1.

   $$\alpha = I_C/I_E \cong 1$$

2. COMMON BASE (CB)

   A method of connecting a transistor into a circuit so that the input signal is applied to the emitter, the output signal taken from the collector and the base is common to the input and output (ac ground).

3. INPUT IMPEDANCE, Z_{in}

   The impedance seen by a signal source looking into the input terminal of an amplifier. In the common base configuration, the input impedance equals r'e.

4. OUTPUT IMPEDANCE, Z_{out}

   The impedance measured at the output terminals of an amplifier when no load is connected. For the common base configuration, the output impedance is equal to the value of the collector resistor, R_C.

5. POWER GAIN (A_p)

   The amount of power amplification achieved by a circuit. It is expressed as $A_p = A_i A_v$ and in the common base circuit, the power gain is expressed as A_v because $A_i \cong 1$.

6. SOURCE RESISTANCE

   The source resistance, R_S, also called the source impedance, is the internal resistance of a signal source that causes the signal voltage to drop when loaded.

ASSIGNMENT

Answer the following multiple choice questions.

1. In the common base amplifier circuit, the element that is at ac ground potential is the:

   a. base.
   b. emitter.
   c. collector.
   d. any of the above.

2. In the common base circuit, the input impedance is _____ and the output impedance is _____.

   a. high; low
   b. low; high
   c. low; low
   d. high; high

3. In the common base amplifier circuit, the voltage gain is _____ and the current gain is _____.

   a. high; high
   b. low; low
   c. low; high
   d. high; low

4. In the common base amplifier circuit, the input signal and the output signal are:

   a. of equal amplitude.
   b. in phase.
   c. 180° out of phase.
   d. none of the above.

5. The major drawback of the common base circuit is its:

   a. low voltage gain.
   b. high input impedance.
   c. high voltage gain.
   d. low input impedance.

You may conclude from the above that the input impedance of the CB amplifier shown in Figure 1 is equal to r'e which is normally low. The result has been severe loading of the source generator, even though it has a low source resistance. With higher source resistances, the drop in input and therefore output voltage, will be more severe.

10.3 MEASURING CB OUTPUT IMPEDANCE

In this part of the experiment, you will measure the output impedance of the CB amplifier and observe that it is high as in the CE configuration.

10. Place switches SA and SB both DOWN and adjust the input signal level to produce an unloaded output voltage (V_{NL}) of 4 volts p-p.

11. Place switch SB in the UP position to place the 3.3K load in the output circuit. Measure and record the loaded (V_{FL}) output voltage.

LOADED OUTPUT VOLTAGE	V_{FL} = V

12. Calculate the measured output impedance, R_{out}, from

$$R_{out} = R_L \frac{(V_{NL} - V_{FL})}{V_{FL}} = (3300) \frac{(4) - (\quad)}{(\quad)}$$

MEASURED OUTPUT IMPEDANCE	R_{out} =

Does the output impedance equal RC as in the common emitter circuit?

13. Adjust the input and output signals on the oscilloscope screen so that each occupies approximately 2 divisions (2 cm).

Compare the phase relationship between the two signals. Are they in phase or 180° out of phase?

Common Base (CB) Amplifier Operation 10

OBJECTIVES

When you finish this experiment you will be able to:

1. Draw the circuit of a common base amplifier with voltage divider bias.
2. Calculate and measure the voltage gain of a common base amplifier.
3. Define the phase relationship between the input and output signals of a common base amplfier.
4. Explain why the current gain of a common base amplifier is approximately one.
5. Calculate and measure the input and output impedances of a common base amplifier.

REFERENCE

CES Lesson J1-10, Common Base (CB) Amplifier Circuits

BACKGROUND

The common base amplifier has the input signal applied to the emitter and the output signal taken from the collector. This experiment uses a voltage divider biased CB amplifier powered with a single voltage source. The voltage gain, input and output impedances are all measured and the input/output phase relationship is observed. This experiment includes 3 parts:

10.1 Measuring CB Voltage Gain
10.2 Measuring CB Input Impedance
10.3 Measuring CB Output Impedance

5. Calculate the amplifier voltage gain from:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{(\quad)}{0.02}$$

MEASURED COMMON BASE VOLTAGE GAIN	A_v =

Observe that the voltage gain of the common base amplifier is high, similar to the common emitter amplifier (without a swamping resistor), as measured earlier in Experiment 3, Common Emitter Amplifier Operation. The CB voltage gain is much higher than the voltage gain of the CC amplifier which was measured as 1 in Experiment 8.

10.2 MEASURING CB INPUT IMPEDANCE

In this part of the experiment you will measure the input impedance of the CB amplifier and observe how the low input impedance loads the signal source.

6. Calculate the CB input impedance which is r'e, from the equation for gain using the measured gain.

$$A_v = \frac{R_C}{r'e}$$

Therefore: $$r'e = \frac{R_C}{A_v} = \frac{3300}{(\quad)}$$ ⟵ from step 5

CB INPUT IMPEDANCE	R_{in} =

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CB	LOW $A_i = \frac{I_C}{I_E} \cong 1 = \alpha$	HIGH $A_v = \frac{R_C}{r'e}$	HIGH $A_p \cong A_v = R_C/r'e$	VERY LOW $Z_{in} = r'e$	HIGH $Z_{out} = R_C$	0°

TABLE 1 - Comparision of CE, CC and CB characteristics.

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7. Common base circuits are used where:

   a. low level high frequency signals are to be amplified.
   b. only low frequency high level signals are encountered.
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   d. high power gain is necessary.

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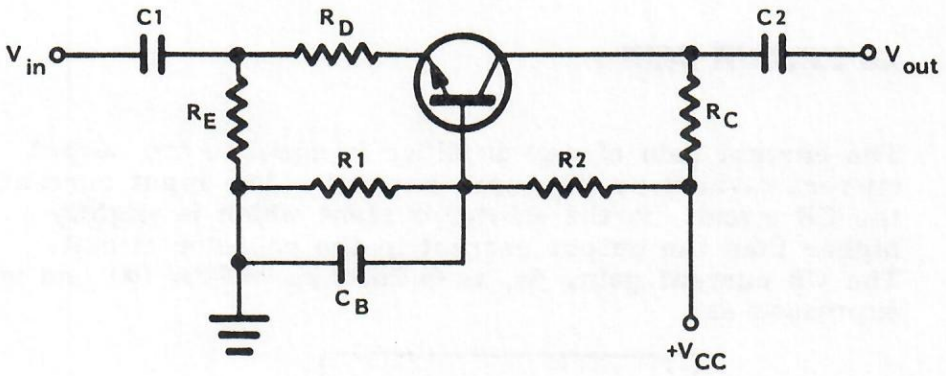

Figure 3 - CB configuration with a swamping resistor, R_D.

CB INPUT IMPEDANCE

The input impedance of the CB amplifier (without a swamping resistor), shown in Figure 1(c) is very low and given by:

$$Z_{in} = R_E // r'e \qquad (2)$$

Because the base is at ac ground, it can be seen that the base-emitter junction is in parallel with R_E (through capacitor C_B). Because r'e is so low ($25/I_E$), and the value of R_E is usually 1 K or more, the input impedance is expressed as:

$$Z_{in} = r'e \qquad (3)$$

Transistor Specification Sheets

INFO SHEET 4

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When you finish this information sheet you will be able to:

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5. Convert from one frequency rating to any other frequency rating form.

DISCUSSION

In all the previous experiments, the only transistor characteristic that was used was beta, the current gain. Even there, circuits were designed to be independent of beta so that all we had to know was the transistor type, NPN or PNP, to design the circuit and, on occasions, whether the transistor was germanium or silicon. The applied voltage was a maximum of 9 volts or 18 volts if the positive and negative voltages were both used. The maximum current that could be obtained was limited by the power supply. The frequencies that were amplified were in the range of 1 Hz to 100 kHz when supplied by the Function Generator or in the range of 1 MHz when used with radio signals. The trainer was designed so that the power source limits could not burn out the transistors.

MAXIMUM RATINGS

If we were to apply 100 volts to any transistor on the trainer, we would expect it to "burn out" and if we were to supply 20 amperes to the transistor we would expect a similar fate. Even if the voltage applied was 20 volts with a resulting 20 mA current, the power dissipated by the transistor would be 4 watts (20 x 200 mA) and a small, low power transistor would not survive. It becomes important, therefore, to know the maximum voltages, currents and power ratings associated with a transistor when designing or repairing equipment.

Common Base (CB) Amplifier Circuits

Lesson No. 10

SCOPE

1. This lesson supports Unit J1-Experiment No. 10, Common Base (CB) Amplifier Operation.

2. The common base amplifier has the input signal applied to the emitter and the output signal taken from the collector. The circuit configuration is described together with the equations for voltage gain, current gain, power gain and input and output impedances.

3. This is the last of the three configurations discussed and therefore a summary of characteristics for all three configurations, CE, CC and CB is presented in table form.

DISCUSSION

The previous experiments described the operation of the common emitter (CE) and common collector (CC) amplifiers. We will now examine the circuit, operation and characteristics of the third configuration, the COMMON BASE (CB). The development of the conventional common base configuration is shown in Figure 1.

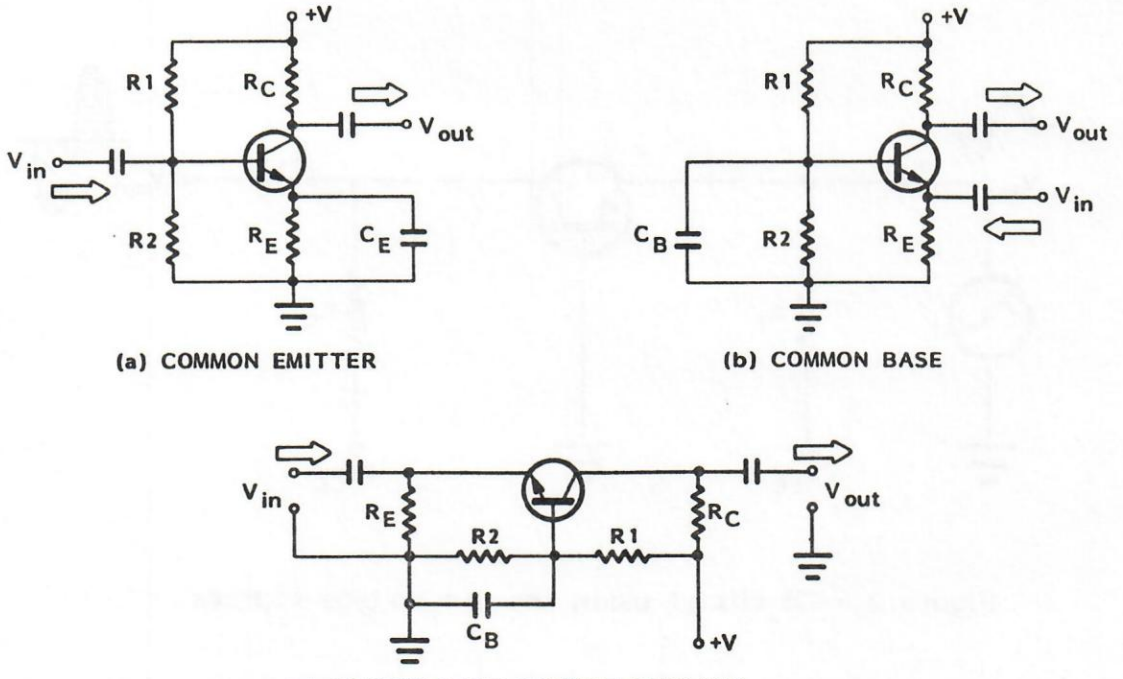


Figure 1 - Development of the common base circuit.

The information provided in a transistor specification sheet falls into seven categories. Five of these categories were covered when diodes were studied and apply equally to transistors since the simplest transistor model consists of two back-to-back diodes (Experiment J1-1). A general listing of these areas is given in Table 1 and, within each area are listed the several variations for transistors. These variations occur because the transistor is a three terminal device and thus there are more leakage paths and voltage breakdown possibilities.

CHARACTERISTIC	DIODE	TRANSISTOR
MAXIMUM POWER OR CURRENT	P - Continuous power dissipation I_F - Maximum forward current	P_D - Maximum power dissipation $I_{C\ max}$ - Maximum allowable collect current
LEAKAGE CURRENT	I_{REV} - Reverse current	I_{cbo} , I_{eco} , I_{ebo} - Leakage currents between E, B and C.
BREAKDOWN VOLTAGE (Reverse biased junctions)	PIV - Peak inverse voltage	$V_{BR\ CBO}$, $V_{BR\ CEO}$, $V_{BR\ EBO}$ - Maximum reverse bias breakdown (BR) voltage
CONDUCTIVITY	V_F - Forward biased junction voltage drop	$V_{CE\ sat}$ - Saturation collector to emitter voltage drop
FREQUENCY RESPONSE	t_{rr} - Reverse recovery time	t_{on} , t_{off} - Delay times f_t - Frequency for unity gain
AMPLIFICATION	Not Applicable	α, β, h_{fb} , h_{fe} , h_{fc} - Current gains
NOISE	Not Applicable	NF - Ratio relating output to input noise

TABLE 1 - Diode and transistor data comparison.

9. The input impedance seen by a generator connected to V_{in} in Figure 8, will be approximately:

   a. 200 K.
   b. 75 K.
   c. 37.5 K.
   d. 31.5 K.

10. In the circuit of Figure 8, if you wish to maintain a high input impedance it is done by:

   a. keeping resistors R1 and R2 as high as possible.
   b. making R3 as high as possible.
   c. using a transistor with the highest possible beta.
   d. all of the above.

11. The output impedance of the circuit in Figure 8, given a source resistance of 30 K and a load resistance of 1 K, is closest to:

   a. 1 K//1 K = 500 ohms.
   b. 150 ohms.
   c. 75 K//75K = 37.5 K.
   d. 300 ohms.

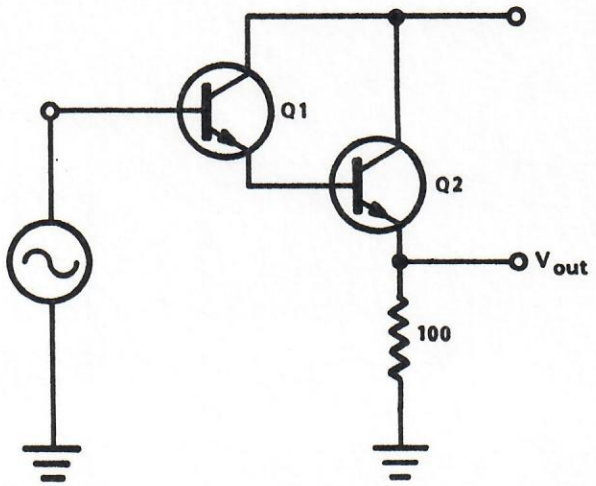


Figure 9 above refers to questions 12 to 15.

12. The circuit shown in Figure 9 is called a:

   a. Cascaded Emitter Follower (CEF).
   b. Compound Common Collector (CCC).
   c. Darlington Pair Amplifier.
   d. Common Emitter Follower.

The collector to emitter saturation voltage, $V_{CE\ sat}$, is much lower than the diode forward voltage drop because the two opposite polarity voltage drops, NP (collector to base) and PN (base to emitter) are now series opposing and partially cancel each other.

CURRENT GAIN AND NOISE

In addition to the first five transistor characteristics, listed in Table 1, that are common to the diode (with some variations), there are two additional transistor characteristics shown that have no diode equivalent. The first is CURRENT AMPLIFICATION, identified as alpha, beta, h_{fe} h_{fb}, or h_{fc}, depending upon the configuration. The second addition is the NOISE FIGURE, NF which refers to the unwanted noise generated in the transistor during the process of amplification and measured as the ratio of the output noise to input noise.

TEMPERATURE EFFECTS

All the characteristics listed in the transistor specification sheets are based on an operating temperature of 25°C (77°F) which is considered to be "room temperature." If a transistor is operated at a temperature above 25°C all the specifications change. The transistor's allowable power dissipation, P_D, must be reduced or DERATED. Also, the leakage currents will increase with temperature. Because the specification sheets give the "Maximum Allowable Ratings," the figures should not be exceeded. In fact, the circuits should be designed so that the transistors operate well below the maximum ratings to provide a safety margin to reduce the possibility that the transistors might eventually fail in use.

Thus, if we expect the equipment to operate at 65°C (140°F) then the increase in temperature, in centigrade, is 65 - 25 = 40°C. The 2N3903 and 2N3904 are both rated for a dissipation of 625 mW at 25°C. For operation at 65°C, they would both have to be derated at 5 mW/°C to:

POWER DISSIPATION AT 65°C (140°F)

$$P_{D\ max} = 625\ mW - \left[\frac{5mW}{°C} \times 40°C \right]$$

MAX. POWER DISSIPATION AT 65°C	$P_{D\ max} = 425\ mW$

ASSIGNMENT

Answer the following multiple choice questions.

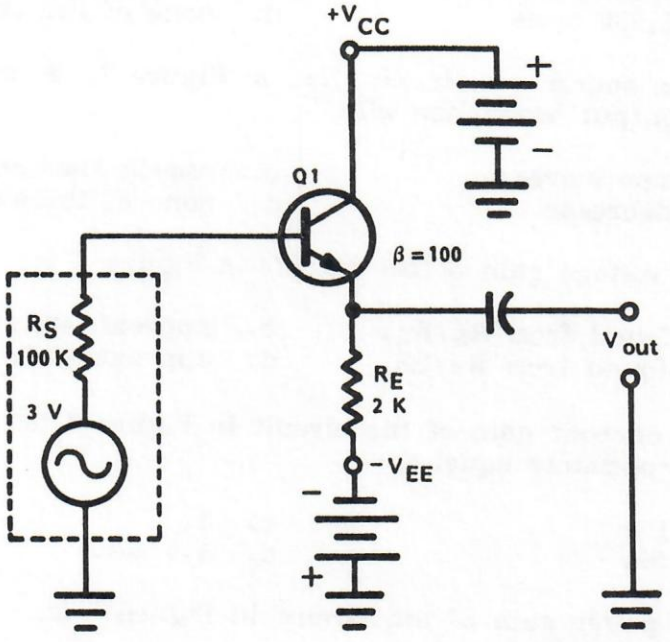


Figure 7 above refers to questions 1 to 8.

1. The amplifier circuit shown in Figure 7 is called a (an):

   a. common emitter.
   b. emitter follower.
   c. common collector.
   d. either b or c.

2. The input impedance at the base of Q1 in Figure 7 is approximately:

   a. 100 K.
   b. 100 ohms.
   c. 200 K.
   d. 2000 ohms.

3. The measured input signal voltage at the base of Q1 in Figure 7 will be:

   a. 3 volts.
   b. 2 volts.
   c. 1 volt.
   d. 0 volts.

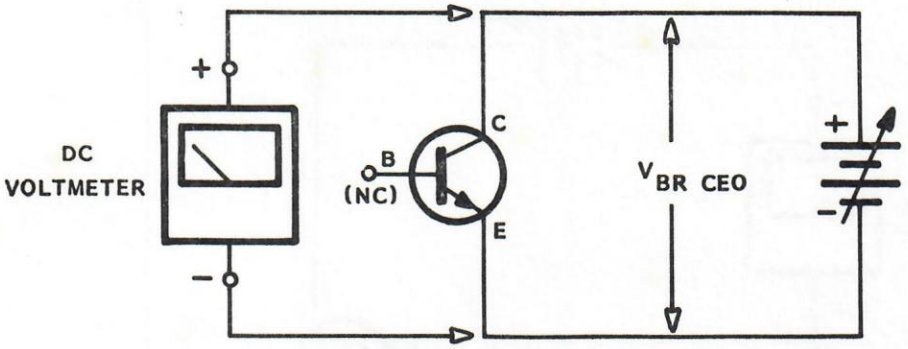


Figure 3 - Breakdown test for $V_{BR\ CEO}$.

Leakage Currents: Transistor leakage current ratings also use the three letter subscript system. There are three leakage current ratings with several variations as shown in Table 3.

RATING	DESCRIPTION
I_{CBO}	Collector Leakage Current: Also called the collector cut-off current, it is the dc collector current with the collector-base junction reverse biased with the emitter floating. It is also called I_{CO}.
I_{CEO}	Collector Leakage Current: Also called the collector cut-off current, it is the dc collector current flow from emitter to collector with the base open.
I_{EBO}	Emitter Leakage Current: Also called the emitter cut-off current, it is the dc emitter current flow with the emitter-base junction reverse biased and the collector floating. It is also called I_{EO}.

TABLE 3 - Transistor current leakage ratings.

The method of measuring I_{CBO} is shown in Figure 4. Note that the B-C junction is reverse biased, which is normal, and the microammeter is measuring the leakage current flow. Note also that the emitter is floating. Other leakage currents are similarly measured with the junctions reverse biased.

KEY TERMS

1. ATTENUATION

   A decrease in the signal strength during its transmission from one point to another. A gain of less than "1."

2. COMMON COLLECTOR CIRCUIT (CC)

   A method of connecting a transistor into a circuit so that the input signal is applied to the base, the output signal is taken from the emitter and the collector is common to the input and output circuit (ac ground).

3. DARLINGTON AMPLIFIER

   Also called a Darlington Pair, it consists of two transistors with their collectors connected directly to the voltage source (V) and the emitter of Q1 connected to the base of Q2. The load is placed in the emitter of Q2. The circuit may be viewed as cascaded common collector amplifiers.

4. DISTORTION

   An undesired change in the output signal waveshape as compared to the input signal waveshape. It is often the result of operating a transistor amplifier in the non-linear region.

5. EMITTER FOLLOWER (EF)

   Another name for the common collector circuit so called because the output signal at the emitter faithfully follows the input signal at the base in voltage variations and phase.

6. INPUT IMPEDANCE, Z_{in}

   The impedance seen by a signal source looking into the input terminals of an amplifier. In the common collector, the input impedance equals $\beta(R_E)$.

A typical value of f_β might be 200 MHz.

When in the CB configuration, the half-power point frequency is defined as the:

Alpha Cut-off Frequency	f_α

Another method of specifying the high frequency performance of a transistor is the GAIN-BANDWIDTH PRODUCT, GBP or f_T. The Gain-Bandwidth Product is the frequency at which the transistor current gain drops to 1, unity. The GBP will be much higher than f_β and slightly less than f_α. When the high frequency performance of a transistor is specified by the GBP, f_T, it may be converted to f_β as shown below.

$$f_\beta = \frac{f_T}{\beta} \qquad (1)$$

Given f_β, f_T can be derived from:

GAIN BANDWIDTH PRODUCT	$f_T = f_\beta\ (\beta)$

(2)

The alpha cut-off frequency, when f_T is known, can be shown to equal:

$$f_\alpha = f_T\ (1.2) \qquad (3)$$

If a transistor has a beta of 200 and a specified gain-bandwidth product of 500 mHz, then f_β could be calculated as:

$$f_\beta = \frac{f_T}{\beta} = \frac{500\ \text{mHz}}{200} = \underline{2.5\ \text{mHz}}$$

With a beta cut-off frequency of only 2.5 MHz, the transistor would be limited to use as an audio amplifier or radio frequency amplifier in an AM radio receiver where the highest frequency to be amplified is 1600 kHz (1.6 mHz). For FM or TV service, a transistor with a considerably higher f_T would have to be used.

TYPICAL TRANSISTOR SPECIFICATION SHEET

The following three pages constitute the spec sheet for the 2N3903 and the 2N3904 silicon transistors and the 2N3904 is used as Q6 and Q7 in the Ed-Lab trainer. The heading of the first page indicates the general purpose or applications of the transistor, in this case switching and amplifier operation. This is followed by a description of the plastic housing characteristics insofar as heat, humidity and light are concerned. The TO-92 case outline, dimensions and base connections are shown in the drawing.

The "Absolute Maximum Ratings at 25°C Free Air Temperature" are listed below the outline drawings. These include the:

Collector-Base Voltage
Collector-Emitter Voltage (with the base open, $V_{BR\ CEO}$)
Emitter-Base Voltage
Continuous Collector Current
Continuous Device Dissipation at (or below) 25°C.

If the maximum device dissipation is 625 mW, it must be derated 5 mW/°C for every degree above 25°C (77°F) up to a maximum of 150°C (302°F).

The "Absolute Maximum Ratings" continue, listing two more quantities: These are:

Storage Temperature Range
Lead Temperature 1/16 inch from case

If the Storage Temperature is higher or lower than the maximum allowable ratings, the transistor could be damaged even though it is only stored and not in an operating circuit.

The Lead Temperature is a problem when a transistor is being soldered into a circuit. The soldering iron should not be held on the connection point long enough to allow the lead temperature to reach 250°C where the lead enters the case; this will overheat and destroy the junction attached to the lead. To prevent this, a device called a HEAT SINK is placed on the transistor lead temporarily to absorb the heat while the transistor lead is being soldered.

The second page of the spec sheet provides the electrical data. Note that there are two data columns, one for the 2N3903 and a second for the 2N3904. The 2N3904 is an improved model compared to the 2N2903 and it is used in the Ed-Lab Trainer. Observe also, that many electrical characteristics listed have Minimum and Maximum ratings and a

TYPES 2N3903, 2N3904, A5T3903, A5T3904
N-P-N SILICON TRANSISTORS

BULLETIN NO. DL-S 7311576, NOVEMBER 1971—REVISED MARCH 1973

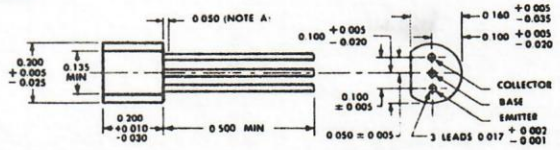
SILECT† TRANSISTORS‡
FOR GENERAL PURPOSE SATURATED-SWITCHING AND AMPLIFIER APPLICATIONS

- **For Complementary Use with P-N-P Types 2N3905, 2N3906, A5T3905, and A5T3906**
- **Rugged One-Piece Construction with In-Line Leads or Standard TO-18 100-mil Pin-Circle Configuration**

mechanical data

These transistors are encapsulated in a plastic compound specifically designed for this purpose, using a highly mechanized process developed by Texas Instruments. The case will withstand soldering temperatures without deformation. These devices exhibit stable characteristics under high-humidity conditions and are capable of meeting MIL-STD-202C, Method 106B. The transistors are insensitive to light.

2N3903, 2N3904

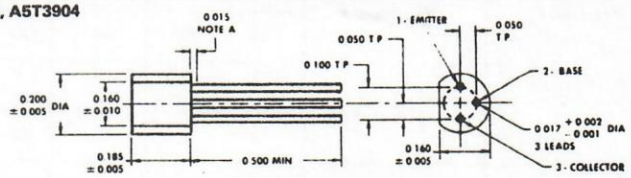


NOTES: A. Lead diameter is not controlled in this area.
B. All dimensions are in inches.

*ALL JEDEC TO-92 DIMENSIONS AND NOTES ARE APPLICABLE

EBC

A5T3903, A5T3904



NOTES: A. Lead diameter is not controlled in this area.
B. Leads having maximum diameter (0.019) shall be within 0.007 of their true positions measured in the gaging plane 0.054 below the seating plane of the device relative to a maximum-diameter package.
C. All dimensions are in inches.

absolute maximum ratings at 25°C free-air temperature (unless otherwise noted)

Collector-Base Voltage	60 V*
Collector-Emitter Voltage (See Note 1)	40 V*
Emitter-Base Voltage	6 V*
Continuous Collector Current	200 mA*
Continuous Device Dissipation at (or below) 25°C Free-Air Temperature (See Note 2)	625 mW§ 310 mW*
Storage Temperature Range	−65°C to 150°C§ −55°C to 135°C*
Lead Temperature 1/16 Inch from Case for 60 Seconds	260°C§ 230°C*

NOTES 1. This value applies between 10 μA and 200 mA collector current when the base-emitter diode is open-circuited.
2. Derate the 625-mW rating linearly to 150°C free-air temperature at the rate of 5 mW/°C. Derate the 310-mW (JEDEC registered) rating linearly to 135°C free-air temperature at the rate of 2.81 mW/°C.

*The asterisk identifies JEDEC registered data for the 2N3903 and 2N3904 only. This data sheet contains all applicable registered data in effect at the time of publication.

†Trademark of Texas Instruments

‡U.S. Patent No. 3,439,238

§Texas Instruments guarantees these values in addition to the JEDEC registered values which are also shown.

USES CHIP N14

TYPES 2N3903, 2N3904, A5T3903, A5T3904
N-P-N SILICON TRANSISTORS

*electrical characteristics at 25°C free-air temperature

PARAMETER		TEST CONDITIONS		2N3903, A5T3903		2N3904, A5T3904		UNIT
				MIN	MAX	MIN	MAX	
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10 μA, I_E = 0		60		60		V
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1 mA, I_B = 0,	See Note 3	40		40		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 μA, I_C = 0		6		6		V
I_{CEV}	Collector Cutoff Current	V_{CE} = 30 V, V_{BE} = −3 V			50		50	nA
I_{BEV}	Base Cutoff Current	V_{CE} = 30 V, V_{BE} = −3 V			−50		−50	nA
h_{FE}	Static Forward Current Transfer Ratio	V_{CE} = 1 V, I_C = 100 μA		20		40		
		V_{CE} = 1 V, I_C = 1 mA		35		70		
		V_{CE} = 1 V, I_C = 10 mA		50	150	100	300	
		V_{CE} = 1 V, I_C = 50 mA	See Note 3	30		60		
		V_{CE} = 1 V, I_C = 100 mA		15		30		
V_{BE}	Base-Emitter Voltage	I_B = 1 mA, I_C = 10 mA	See Note 3	0.65	0.85	0.65	0.85	V
		I_B = 5 mA, I_C = 50 mA			0.95		0.95	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_B = 1 mA, I_C = 10 mA	See Note 3		0.2		0.2	V
		I_B = 5 mA, I_C = 50 mA			0.3		0.3	
h_{ie}	Small-Signal Common-Emitter Input Impedance	V_{CE} = 10 V, I_C = 1 mA, f = 1 kHz		1	8	1	10	kΩ
h_{fe}	Small-Signal Common-Emitter Forward Current Transfer Ratio			50	200	100	400	
h_{re}	Small-Signal Common-Emitter Reverse Voltage Transfer Ratio			0.1×10^{-4}	5×10^{-4}	0.5×10^{-4}	8×10^{-4}	
h_{oe}	Small-Signal Common-Emitter Output Admittance			1	40	1	40	μmho
$\|h_{fe}\|$	Small-Signal Common-Emitter Forward Current Transfer Ratio	V_{CE} = 20 V, I_C = 10 mA, f = 100 MHz		2.5		3		
f_T	Transition Frequency	V_{CE} = 20 V, I_C = 10 mA, See Note 4		250		300		MHz
C_{obo}	Common-Base Open-Circuit Output Capacitance	V_{CB} = 5 V, I_E = 0, f = 100 kHz to 1 MHz			4		4	pF
C_{ibo}	Common-Base Open-Circuit Input Capacitance	V_{EB} = 0.5 V, I_C = 0, f = 100 kHz to 1 MHz			8		8	pF

NOTES: 3. These parameters must be measured using pulse techniques. t_w = 300 μs, duty cycle ≤ 2%.

4. To obtain f_T, the $|h_{fe}|$ response with frequency is extrapolated at the rate of −6 dB per octave from f = 100 MHz to the frequency at which $|h_{fe}|$ = 1.

*operating characteristics at 25°C free-air temperature

PARAMETER		TEST CONDITIONS	2N3903 A5T3903		2N3904 A5T3904		UNIT
			MIN	MAX	MIN	MAX	
$\overline{NF}$	Average Noise Figure	V_{CE} = 5 V, I_C = 100 μA, R_G = 1 kΩ, Noise Bandwidth = 15.7 kHz, See Note 5		6		5	dB

NOTE 5: Average Noise Figure is measured in an amplifier with response down 3 dB at 10 Hz and 10 kHz and a high-frequency rolloff of 6 dB/octave.

*The asterisk identifies JEDEC registered data for the 2N3903 and 2N3904 only.

TYPES 2N3903, 2N3904, A5T3903, A5T3904
N-P-N SILICON TRANSISTORS

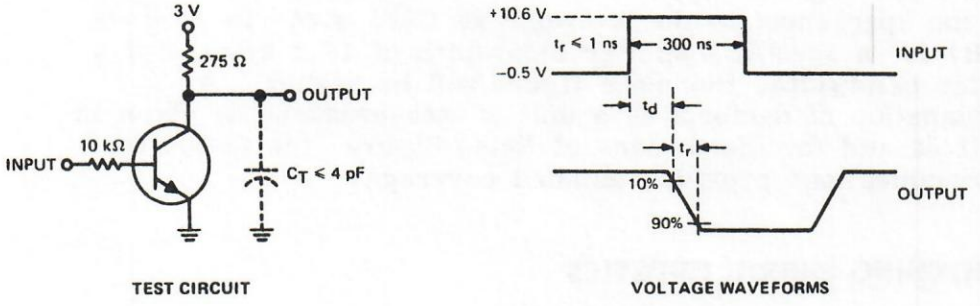
*switching characteristics at 25°C free-air temperature

PARAMETER		TEST CONDITIONS†			2N3903 A5T3903 MAX	2N3904 A5T3904 MAX	UNIT
t_d	Delay Time	I_C = 10 mA,	$I_{B(1)}$ = 1 mA,	$V_{BE(off)}$ = −0.5 V,	35	35	ns
t_r	Rise Time	R_L = 275 Ω,		See Figure 1	35	35	ns
t_s	Storage Time	I_C = 10 mA,	$I_{B(1)}$ = 1 mA,	$I_{B(2)}$ = −1 mA,	175	200	ns
t_f	Fall Time	R_L = 275 Ω,		See Figure 2	50	50	ns

†Voltage and current values shown are nominal; exact values vary slightly with transistor parameters. Nominal base current for delay and rise times is calculated using the minimum value of V_{BE}. Nominal base currents for storage and fall times are calculated using the maximum value of V_{BE}.

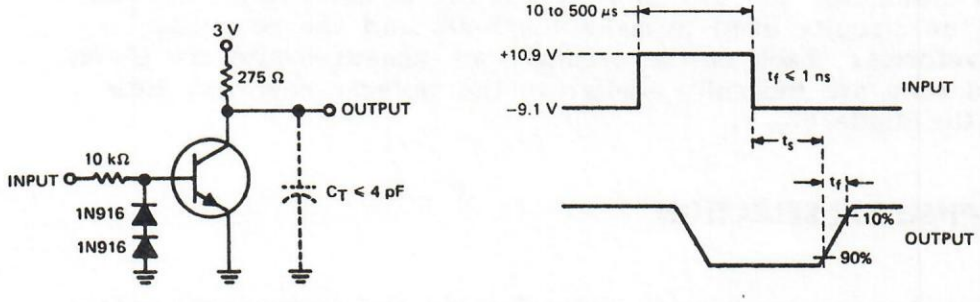
*The asterisk identifies JEDEC registered data for the 2N3903 and 2N3904 only.

PARAMETER MEASUREMENT INFORMATION



TEST CIRCUIT VOLTAGE WAVEFORMS

FIGURE 1–DELAY AND RISE TIMES



TEST CIRCUIT VOLTAGE WAVEFORMS

FIGURE 2–STORAGE AND FALL TIMES

NOTES: a. The input waveforms are supplied by a generator with the following characteristics: Z_{out} = 50 Ω, duty cycle = 2%.
b. Waveforms are monitored on an oscilloscope with the following characteristics: t_r ≤ 1 ns, R_{in} = 10 MΩ, C_{in} ≤ 4 pF.

typical transistor may exhibit a value anywhere between these two limits. As an example, h_{ie}, as shown for the 2N3904, may fall between 1 K and 10 K. Note also that the only frequency rating is the gain-bandwidth product, f_T, which is equal to 300 mHz. Thus, to determine f_β, the high frequency cut-off in the CE configuration, we use equation (1) and so:

$$f_\beta = \frac{f_T}{\beta} = \frac{300 \text{ mHz}}{250} = \underline{1.2 \text{ mHz}}$$

NOISE FIGURE

The Noise Figure of the transistor listed on the second page of the spec sheet is the Average NF ($\overline{NF}$) given in decibels (dB) for a specific amplifier bandwidth of 15.7 kHz. For a wider bandwidth, the noise figure will be higher. An explanation of decibels as a unit of measurement, is given in Unit J2 and for discussions of Noise Figure, the lesson on Communications provides detailed coverage.

SWITCHING CHARACTERISTICS

Page three of the spec sheets covers the switching characteristics of the transistor. Page three shows how fast the transistor can switch from cut-off to saturation, as well as the circuits used to make the tests and the response waveforms. Each of the critical time measurements are given and they are basically similar to the reverse recovery time of the diode (t_{rr}).

TRANSISTOR SELECTION

When designing a circuit and selecting the proper transistor to use, the ratings listed in the specification sheet must be reviewed and taken into account to make sure that the circuit will achieve the designed gains and frequency response. It is also necessary to make certain that the desired voltage, current and power ratings have not been exceeded in order to assure long transistor life. When selecting the transistor to be used, we must consider the purpose for which it was intended. There are some transistors designed as general purpose devices for use in audio, digital and radio circuits. Others are designed for special low noise operation and others are for very high frequency operation, and others are for high power output.

In any particular circuit application, there may be many different types of transistors that could be used to achieve the design performance. Selection of the transistor will be based on many factors including availability, cost and standardization. The Ed-Lab Trainer transistors are general purpose types suitable for audio amplifiers, radio frequency circuits, digital switching circuits and low power audio and radio frequency amplification.

CONCLUSIONS

We have learned from this information sheet that:

1. Five of the transistor specifications are the same as those used for diodes.

2. The Breakdown Voltages and Leakage Currents each have three ratings because there are three possible lead combinations for a transistor.

3. The maximum power dissipation, P_D, is the heat developed by the reverse biased collector-base junction.

4. The $V_{CE\ sat}$ rating of a transitor is a measure of its conductivity. The lower the voltage, usually several tenths of a volt, the better the conductivity.

5. Transistors require two additional ratings which diodes do not have; these are current gain and Noise Figure, NF. NF is a rating of how much noise the transistor generates when amplifying.

6. Transistor spec sheets provide "Maximum Allowable Ratings" at 25°C, room temperature.

7. Transistors should be operated below their maximum ratings as a safety margin for greater reliability.

8. When the transistor is operated above 25°C, its allowable P_D must be derated, as directed in the spec sheet, at so many mW per °C above 25°C.

9. The leakage currents and breakdown voltages use a three letter subscript system with the first two letters indicating the junction and the third letter, O, S or R, indicating the state of the third lead.

10. The breakdown voltages are $V_{BR\ CBO}$; $V_{BR\ CEO}$ and $V_{BR\ EBO}$.

11. The leakage currents are I_{CBO}, I_{CEO} and I_{EBO}.

12. The transistor current gain figures given in the data sheet are measured at 1 kHz.

13. As the input frequency is increased, at a critical value of frequency, the gain will start to drop. When I_{out} or V_{out} drops to 70.7% of that at 1 kHz, you have reached f_β.

14. When the frequency is increased until the gain is equal to unity, 1, you have reached f_T, the Gain Bandwidth Product (GBP).

15. The equations for frequency relationships are:

    Alpha Cut-off Level = $\alpha(0.707)$
    Beta Cut-off Level = $\beta(0.707)$

    $$f_\beta = \frac{f_T}{\beta} \qquad f_\alpha = f_T\ (1.2) \qquad f_T = f_\beta\ (\beta)$$

16. Transistor wire leads must never be overheated when being soldered into a circuit or the junction connected to the overheated lead will be destroyed.

17. The average noise figure, $\overline{NF}$, is given in dB (decibels) over a specific bandwidth.

KEY TERMS

1. ALPHA CUT-OFF FREQUENCY, f_α

   In a CB amplifier, the frequency at which the output drops to 0.707 of the mid-frequency output.

2. BETA CUT-OFF FREQUENCY, f_β

   In a CE amplifier, the frequency at which the output drops to 0.707 of the mid-frequency output.

3. BREAKDOWN VOLTAGE, V_{BR}

   The maximum reverse bias voltage across a PN junction before breakdown occurs.

4. COLLECTOR CUT-OFF CURRENT

   A condition in which the only collector current flowing is leakage current.

5. DATA SHEET

   A listing of all the characteristics of an electrical or electronic device on one or more pages, provided by the device manufacturer.

6. DERATING

   All transitor maximum ratings are given at 25°C. When operating above 25°C, these ratings must be reduced or "derated" proportionately to maintain or improve device reliability.

7. f_T

   The frequency at which the transistor gain drops to unity, 1. Also called the gain bandwidth product, GBP.

8. GAIN BANDWIDTH PRODUCT, GBP

   Also known as f_T. See 7 above.

9. HEAT SINK

A large metal area added to some part of the transistor to draw off heat thus protecting the semiconductor junctions from overheating.

10. I_{CBO}

The dc leakage current from collector to base when reverse biased and the emitter is open.

11. I_{CEO}

The dc leakage current from collector to emitter when reverse biased and the base is open.

12. I_{EBO}

The dc leakage current from emitter to base when reverse biased and the collector is opened.

13. I_F

The current that flows across a forward biased PN junction. Normally, this is a diode rating only.

14. I_{REV}

The current that flows across a reverse biased PN junction. Also known as leakage current.

15. LEAKAGE CURRENT

See 14 above.

16. MAXIMUM ALLOWABLE RATINGS

As listed for a diode or transistor, the highest current or voltage that may be applied to the device when it is operated at 25°C.

17. MAXIMUM POWER DISSIPATION, P_D

The highest allowable power a device may dissipate and still operate without the danger of burn-out.

18. NOISE FACTOR, NF

The ratio of the total noise at the output to the total noise at the input over a specific bandwidth. Also called the average Noise Factor and indicated as $\overline{NF}$. Sometimes referred to as the Noise Figure.

19. REVERSE RECOVERY TIME, t_{rr}

The time required for a PN junction to reach the desired level of current after being switched from forward to reverse biased state or from reverse to forward biased state.

20. SPECIFICATION SHEET

See No. 5, Data Sheet.

21. SWITCHING TRANSISTOR

A transistor designed to act as an On-Off switch, going from cut-off to saturation and back to cut-off as necessary. Most switching transistors may also be used as amplifiers.

22. V_{BR}

See No. 3, Breakdown Voltage.

23. $V_{CE\ sat}$

The voltage drop from collector to emitter when the transistor is in saturation. The lower this voltage, normally several tenths of a volt, the better the transistor conductivity.

24. V_F

The voltage drop across a PN junction when forward biased. Silicon has a drop of 0.7 volts and germanium, a drop of 0.3 volts.

ASSIGNMENT

Answer the following multiple choice questions.

1. Which of the following transistor ratings does not have an equivalent diode rating?

   a. Power Dissipation, P_D
   b. Leakage Current
   c. Voltage Breakdown
   d. Noise Figure

2. The maximum power dissipation of a transistor, P_D, is a rating of the heat that is developed in the:

   a. emitter-base junction.
   b. emitter lead when it is being soldered.
   c. collector-base junction.
   d. collector lead when it is being soldered.

3. The conductivity of a transistor is indicated by the rating:

   a. V_F.
   b. $V_{CE\ sat}$.
   c. P_D.
   d. h_{oe}.

4. The breakdown voltage ratings specified in the transistor data sheets:

   a. are the maximum allowable values.
   b. may not be exceeded.
   c. should be reduced for reliable operation.
   d. all of the above.

5. Given a P_D of 500 mW at 25°C and a derating factor of 5 mW/°C, the maximum allowable P_D at 30°C is:

   a. 475 mW.
   b. 525 mW.
   c. 470 mW.
   d. 505 mW.

6. The breakdown voltage between the base and the collector with the emitter open, is indicated by:

   a. I_{CBO}.
   b. I_{CBS}.
   c. $V_{BR\ ICEO}$.
   d. $V_{BR\ CBO}$.

7. Transistor gain data is normally measured at:

   a. 1 kHz.
   b. 1 mHz.
   c. cut-off.
   d. saturation.

8. Given an f_T of 300 mHz, a beta of 110, an alpha of 0.991 and a P_D of 350 mW, the value of f_β is closest to:

   a. 300 mHz.
   b. 350 mHz.
   c. 2.73 mHz.
   d. none of the above.

9. For the data provided in question 8 above, the alpha cut-off frequency is:

   a. 300 mHz.
   b. 360 mHz.
   c. 2.73 mHz.
   d. 650 mHz.

10. Given an f_β of 3.70 mHz for a transistor and a beta of 125, the transistor frequency response at unity is:

    a. 3.70 mHz.
    b. 125 mHz.
    c. 462.5 mHz.
    d. none of the above.

THE 2N3903/2N3904 DATA SHEET INCLUDED IN THIS INFORMATION SHEET IS REQUIRED IN ORDER TO ANSWER THE FOLLOWING QUESTIONS.

11. The average value of h_{fe} for the 2N3904, as specified in the data sheet, is:

    a. 100.
    b. 400.
    c. 250.
    d. 500.

12. The minimum value of h_{fe} for the 2N3903, as specified in the data sheet, is:

    a. 50.
    b. 125.
    c. 200.
    d. 250.

13. The Gain-Bandwidth Product for the 2N3903, as specified in the data sheet, is:

    a. equal to h_{oe}, 5×10^{-4}.
    b. equal to h_{FE}, 150 mHz.
    c. f_T, 250 mHz.
    d. not listed at all.

14. Using the data listed for the 2N3904 in the specification sheet, the average value of f_β is closest to:

    a. 300 mHz.
    b. 312 mHz.
    c. 250 mHz.
    d. 1.2 mHz.

15. If the 2N3903 is operated at 32°C and is rated for 625 mW at 25°C, its maximum allowable power dissipation, according to the spec sheet, will be:

    a. 625 mW.
    b. 590 mW.
    c. 135 mW.
    d. none of the above.